Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, Southeastern Utah and Southwestern Colorado

By Steven M. Condon

EVOLUTION OF SEDIMENTARY BASINS—PARADOX BASIN
A.C. Huffman, Jr., Project Coordinator

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Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, Southeastern Utah and Southwestern Colorado

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ABSTRACT

The Cutler Formation is composed of thick, arkosic, alluvial sandstones shed southwestward from the Uncompahgre highlands into the Paradox Basin. Salt tectonism played an important role in deposition of the Cutler in some areas. In the northeast part of the basin, more than 8,000 ft, and as much as 15,000 ft, of arkose was trapped between rising salt anticlines—this arkose is thin to absent over the crests of some anticlines. In the western and southern parts of the basin, the Cutler is recognized as a Group consisting of, in ascending order: the lower Cutler beds, Cedar Mesa Sandstone, Organ Rock Formation, White Rim Sandstone, and De Chelly Sandstone. The aggregate thickness of these formations is less than 2,000 ft. The formations of the Cutler Group were deposited in a complex system of alluvial, eolian, and marine environments characterized by abrupt vertical and lateral lithologic changes. The basal Cutler is Pennsylvanian in age, but the bulk of the Group was deposited during the Permian. The Cutler is conformably underlain by the Pennsylvanian Hermosa Group across most of the basin. It is overlain unconformably by the Permian Kaibab Limestone in the western part of the Paradox Basin. The Cutler or Kaibab are overlain unconformably by the Triassic Moenkopi or Chinle Formations.

INTRODUCTION

This study was funded as a part of the U.S. Geological Survey's Evolution of Sedimentary Basins Program. The Paradox Basin, located in southeastern Utah and southwestern Colorado, was the subject of a multidisciplinary stratigraphic, sedimentologic, geochemical, and structural investigation. In this report, I describe the regional geology of the Pennsylvanian and Permian Cutler Group and Kaibab Limestone in the Paradox Basin, based mainly on the study of geophysical well logs and outcrop data.

To many people, the canyon country of southeastern Utah and northern Arizona epitomizes the Permian of the Southwestern United States. The canyons and mesas of Canyonlands National Park and the spires and monoliths of Monument Valley are associated with Permian rocks, the Cutler Group in particular. Some reports, such as Wengerd and Matheny (1958) and Baars (1962), have previously demonstrated that the lower part of the Cutler is, however, Pennsylvanian, and this report describes rocks at the Systemic boundary in some detail. In parts of the Paradox Basin, the position of the basal contact of the Cutler is controversial. Once regarded as an unconformable Systemic boundary, it now is interpreted by some as gradational, and the position of the Pennsylvanian-Permian boundary is also questioned. The correlation of younger Permian rocks has been relatively more straightforward; there is, however, substantial disagreement concerning the depositional environments of some units. The arguments are summarized in this report.

Acknowledgments.—Jean Dillinger digitized the base maps used for the maps presented here. Critical reviews by J.E. Huntoon and J.D. Stanesco were of great help in improving the manuscript. Discussions of Pennsylvanian, Permian, and Triassic rocks with J.A. Campbell, R.F. Dubiel, K.J. Franczyk, A.C. Huffman, Jr., J.E. Huntoon, and J.D. Stanesco were very helpful in my gaining an understanding of those units.

GEOGRAPHIC AND STRUCTURAL SETTING

The Paradox Basin is an oval area in southeastern Utah and southwestern Colorado that, for this study, is defined by the maximum extent of halite and potash salts in the Middle Pennsylvanian Paradox Formation (fig. 1, pl. 1). Using this definition, the basin has a maximum northwest-southeast length of about 190 mi, and a northeast-southwest width of about 95 mi. The Paradox Basin, as thus recognized, is in the central part of the Colorado Plateau. The shape of the basin was modified and obscured by later tectonic events, primarily the Laramide orogeny. Today, the basin has been dissected in places by uplift of the Colorado Plateau and by downcutting of the Colorado River and its tributaries. The basin is primarily a Pennsylvanian feature that accumulated thick deposits of carbonate, halite, potash, sandstone, and arkose in response to tectonic downwarping and simultaneous uplift along its northeastern border. In this report, I focus on the Pennsylvanian and Permian stratigraphic units that overlie the salt, even though the depositional limits of those units do not correspond to the limit of salt. The name “Paradox Formation” originated with Baker and others (1933) for exposures of the unit in Paradox Valley, Montrose County, Colorado. The valley and town of Paradox were probably named because the Dolores River cuts through the south valley wall, runs transversely across the valley at right angles to the northwest trend of the valley, and exits through the north valley wall. The relation of the river to the valley is thus, seemingly, a paradox (Hite and Buckner, 1981).

The basin is bordered on the northeast by the Uncompahgre Plateau, a broad anticline cored by Precambrian rocks and faulted along its southwestern side (fig. 2). The east side of the basin is bounded by the San Juan dome, an area that is covered, in part, by Tertiary volcanic rocks. In the Needle Mountains, a prominent feature of the southern San Juan dome, Precambrian rocks are widely exposed. The southeast end of the basin is defined by the northeast-trending Hogback monocline that extends southwestward from the Durango, Colo., area through northwestern New Mexico. The southern and southwestern border of the Paradox Basin is rather poorly defined topographically, extending northwestward from Four Corners (the junction of Utah, Colorado, New Mexico, and Arizona) across the Monument upwarp to the Henry Basin. The northwest side is bounded by the San Rafael Swell, and the far northern end of the basin merges with the southern end of the Uinta Basin.

Structural and topographic features of the Paradox Basin are very diverse. The northern part of the basin has been termed the “Paradox fold and fault belt” (Kelley, 1958b). This area consists of a series of roughly parallel, northwest-trending faults, anticlines, and synclines. The northeastern part of this division is most complexly folded, and salt from the Paradox Formation has risen diapirically to the surface. Dissolution of salt in the center of some anticlines in this region has caused down-faulting and the formation of grabens along the anticlinal crests. Rocks as old as Pennsylvanian are exposed in the cores of some of the anticlines, and remnants of Cretaceous rocks are present in some synclines and in collapsed blocks within some anticlines. The southwestern part of the fold and fault belt is also faulted and folded but lacks the complex piercement structures of the northeastern part.

South of the fold and fault belt are the Blanding Basin and the Four Corners platform (fig. 2). The Blanding Basin is a generally undeformed area in which Jurassic and Cretaceous rocks are at the surface. The Four Corners platform is a structurally high bench capped by Cretaceous rocks that separates the Paradox and San Juan Basins. The Hogback monocline defines the southeast side of the Four Corners platform.

The extreme southwestern part of the Paradox Basin is coincident with the Monument upwarp. This area consists of deep canyons and high mesas that provide the setting for part of Canyonlands National Park, Natural Bridges National Monument, and other recreation and cultural-resource areas. The upwarp trends generally north and is a broad anticline. It is bounded on the east by the steeply dipping Comb Ridge monocline and merges to the west with the Henry Basin across the White Canyon slope. A northeast-trending anticline along the Colorado River is an extension of the Monument upwarp that projects into the fold and fault belt. Permian and some Pennsylvanian rocks are widely exposed on the upwarp and along the river.

Adding to the picturesque qualities of the Paradox Basin are intrusive rocks of the La Sal, Abajo, and Sleeping Ute Mountains that lie within the basin, and intrusive centers such as the Henry, Carrizo, La Plata, Rico, and San Miguel Mountains in surrounding areas. These intrusive rocks are Late Cretaceous to Tertiary in age, and their emplacement deformed the enclosing sedimentary rocks into broad domes.

The current structural configuration of the basin and surrounding area is shown on plate 2, a structure contour map drawn on the base of the Cutler Group or Formation. This horizon was chosen because the data set for the horizon is the most complete for any stratigraphic unit discussed in this report. Older stratigraphic units are generally less suitable because of the fewer wells that penetrated those units, and younger stratigraphic units are commonly eroded and incomplete, making them less useful for a structure contour map.

Plate 2 shows, in circled numbers clockwise from upper left (1) the high area of the San Rafael Swell, (2) the high area of the Uncompahgre Plateau, flanked on its southwest by the deepest part of the Paradox Basin, (3) McElmo dome west of Cortez, Colo., (4) the low area of the San Juan Basin in northwestern New Mexico, (5) the high area of the northern Defiance Plateau in northeastern Arizona, (6) the high area of the Monument upwarp in southeastern Utah, and (7) the low area of the Henry Basin. The sharp flexure of Comb Ridge monocline is clearly evident on the eastern side of the Monument upwarp. Also evident is the structural nose that extends northeastward from the northern end of the Monument upwarp along the Colorado River into the fold and fault belt. Northwest-trending contours in the northeastern part of the basin are evidence of the salt anticlines in the fold and fault belt. Because of the relatively widely spaced control points, offsets on faults are not shown on this map.

PREVIOUS STUDIES AND NOMENCLATURE

The remoteness and inaccessibility of much of the Paradox Basin served to isolate it from the scrutiny of geologists until the latter half of the 19th century. Powell’s historic voyages down the Green and Colorado Rivers were the first detailed accounts of the area (Powell, 1875). The Henry

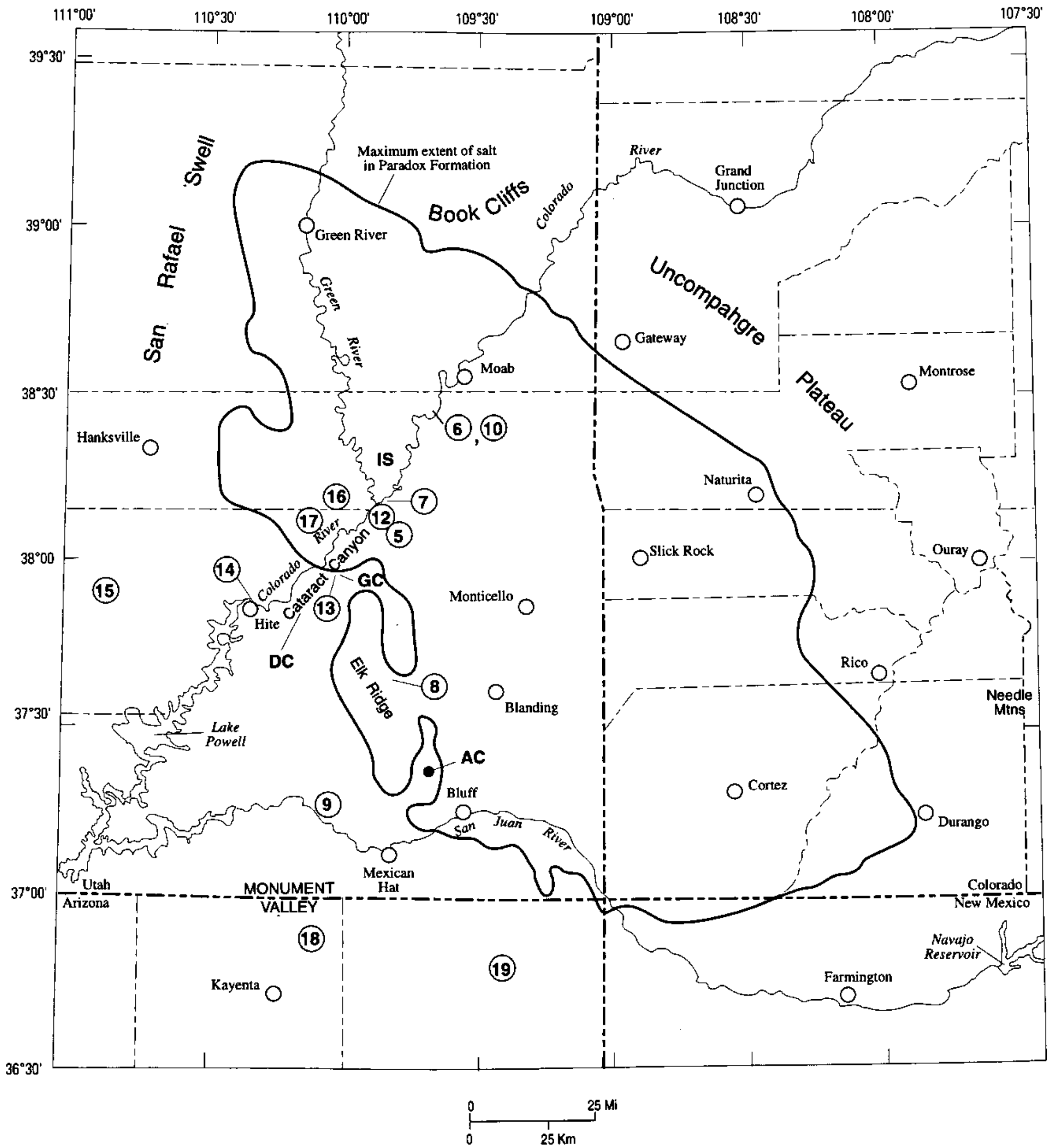


Figure 1. Map showing geographic features of the Paradox Basin and adjacent areas. AC, Arch Canyon; DC, Dark Canyon; GC, Gypsum Canyon; IS, Island in the Sky district of Canyonlands National Park. Circled numbers refer to other figures in this report that are photographs of outcrops or that indicate locations of well logs.

Mountains, just west of the basin, were the last major mountains discovered in the American West.

Whitman Cross and his associates studied the rocks of the San Juan Mountains of southwestern Colorado at the beginning of the 20th century and were among the first to describe the Permian rocks outcropping in that area. The Cutler Formation was named by Cross and others (1905) for exposures along Cutler Creek, 4 mi north of Ouray, Colo. It was considered provisionally Permian in age due to a lack of fossils. The Rico Formation was named by Cross and Spencer (1900) and was considered Pennsylvanian and Permian in age. The Rico was thought to represent beds transitional between the largely marine Hermosa Formation or Group below and the continental Cutler Formation above.

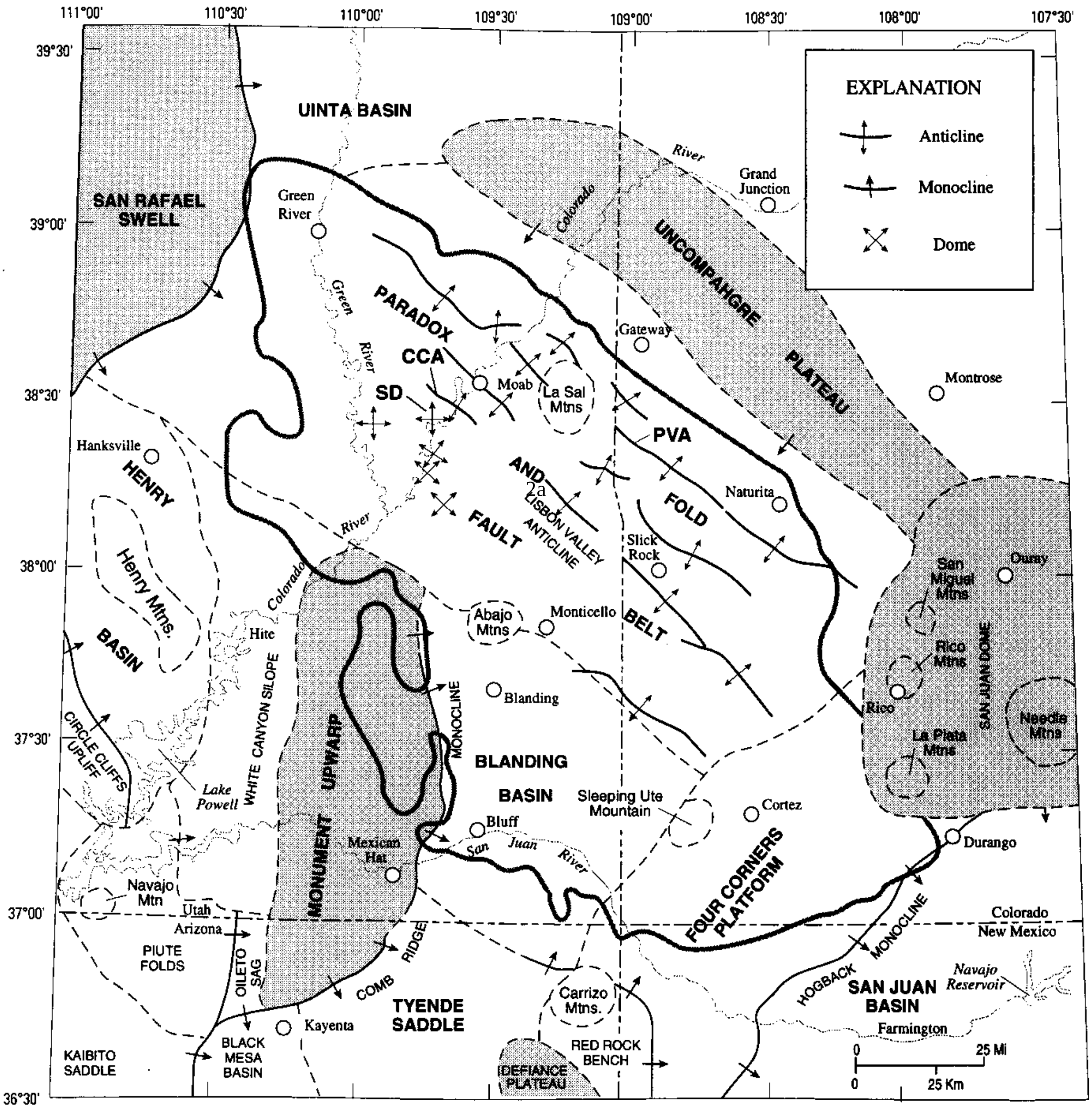


Figure 2. Map showing structural elements of the Paradox Basin and adjacent areas. Dashed lines indicate transitional or indefinite boundaries between elements. PVA, Paradox Valley anticline; CCA, Cane Creek anticline; SD, Shafer dome. Modified from Kelley (1958a, 1958b).

Interest in the water, mineral, and oil and gas resources of southeastern Utah prompted more geologic studies during the early 20th century. Baker and Reeside (1929) defined the units of the Cutler in southeastern Utah and introduced names that are still in use today. In their terminology, the Cutler Formation included, from bottom to top, the Halgaito tongue, Cedar Mesa Sandstone member, Organ Rock tongue, De Chelly Sandstone member, White Rim Sandstone member, and Hoskinnini tongue. The Rico Formation was also recognized in southeastern Utah and was considered Permian in age. Key reports from this period include Longwell and others (1923), Baker and others (1927, 1936), Gilluly and Reeside (1928), Baker and Reeside (1929), Gilluly (1929), Baker (1933, 1936, 1946), Dane (1935), Gregory (1938), and McKnight (1940). These studies were directed mainly toward mapping the surface rocks and structures because of the paucity of deep drilling in the basin at that time. They did provide the basic geologic framework of the basin, which has been refined by subsequent geologic studies.

One of the oldest oil fields in Utah was discovered in 1908 at Mexican Hat (Lauth, 1978); wildcat drilling took place in many areas of the basin through the mid-1950's. Discovery of the giant field at Aneth, southeast of Bluff, Utah, in 1956 (Matheny, 1978) accelerated deep drilling in the basin. Wengerd and Strickland (1954) and Wengerd and Matheny (1958) used the newly drilled deep wells to integrate the geology of Pennsylvanian and Permian units throughout the Four Corners area. Wengerd and Matheny (1958) raised the Cutler to Group rank and, additionally, included what they called the "Rico transitional facies" in the Cutler. The Rico was thought to be of both Pennsylvanian and Permian age.

Baars (1962) presented regional correlations of Permian units of the southern Colorado Plateau. He used most of the terminology introduced by Baker and Reeside (1929) and modified by Wengerd and Matheny (1958) for the Cutler. Baars differed from previous workers mainly in his rejection of the concept of the Rico as a transitional unit between Pennsylvanian and Permian strata. On the basis of field studies by Shell Oil Co. in the 1950's, Baars (1962) recognized a regional unconformity between the Hermosa Group and the Cutler Group. In addition, he formally named the Elephant Canyon Formation for a succession of Permian (Wolfcampian) carbonates in the northwestern part of the Paradox Basin. The Elephant Canyon was described as grading laterally into the Halgaito Formation and interfingering with the overlying Cedar Mesa Sandstone. Baars (1962) defined the Elephant Canyon as entirely Permian in age, but he recognized that the base of the undivided Cutler along the Uncompahgre front was likely Pennsylvanian.

This system of nomenclature was widely accepted and used until Loope (1984), Loope and others (1990), and Sanderson and Verville (1990) questioned the presence of an unconformity beneath the Elephant Canyon. Furthermore, some strata in the Elephant Canyon that were considered Permian in age by Baars (1962, 1987) were interpreted as Pennsylvanian (Missourian and Virgilian) by Sanderson and Verville (1990). Loope (1984) and Loope and others (1990) recommended abandonment of the name "Elephant Canyon Formation." They assigned the lower part of the Elephant Canyon to the underlying Hermosa Group and renamed the upper part the "lower Cutler beds." The Hermosa was considered Pennsylvanian and the lower Cutler beds Permian. In this report, I present regional cross sections wherein I show my correlations of this problematic interval in the subsurface of the Paradox Basin.

Due to the exceptional exposures of the Cutler in the Canyonlands area of southeastern Utah, there are many theses and reports dealing with this stratigraphic interval. Many of these reports are cited below in discussions of individual rock units. Of particular note is Lohman (1974), whose report includes many color photographs of rocks in Canyonlands National Park. Additional data are summarized in Dubiel, Huntoon, Condon, and Stanesco (1996) and Dubiel, Huntoon, Stanesco, and others (1996).

METHODS

DATA

The main sources of data for this study are geophysical logs from wells drilled throughout the Paradox Basin and surrounding areas (Appendix 1). A collection of paper logs was purchased and was used as the basis for the correlations and maps presented here. Types of logs include gamma-ray, neutron, spontaneous potential, resistivity, conductivity, and interval transit time (sonic). A total of 202 well logs were used for this study.

Supplementing the geophysical logs were sample logs from the American Stratigraphic Company (AMSTRAT). These sample logs were used to match specific lithologies to the geophysical log responses. The logs were invaluable in working out correlations of the lower part of the Cutler Group.

A third major source of data was a database of petroleum exploration wells, compiled by Rocky Mountain Geological Databases, Inc., which is mainly concerned with Pennsylvanian and older stratigraphic units. This database provided a consistent top for the Hermosa Group.

Other sources of data were reports concerning Permian rocks in the Paradox Basin area. Surface rocks have been studied previously by other geologists, and thus lithologies and thicknesses of outcropping units in areas not visited by the author were available (Appendix 2). Data were collected from descriptions of 97 outcrop areas. Published isopach maps and cross sections of subsurface units were also consulted to see how other geologists portrayed the units.

I examined outcrops of Permian and adjacent rocks throughout the Paradox Basin. Localities visited included much of Canyonlands National Park, the adjacent Glen Canyon National Recreation area, the San Rafael Swell, the Monument upwarp and the canyon of the San Juan River, the area of salt anticlines in the northeastern part of the basin, and the Permian outcrops that flank the Needle Mountains in southwestern Colorado.

CONTOUR MAPS

The isopach and structure maps compiled for this report were constructed using a program called Interactive Surface Modeling (ISM), formerly marketed by Dynamic Graphics, Inc. A base map was digitized to provide a geographic base for the other maps, and then individual files containing location and thickness data were gridded and contoured. Several figures in this report show log curves with picks of geologic units. These picks were made by me and are the data that were compiled into the isopach and structure maps. The projection of the maps is Lambert conformal conic based on standard parallels 33° and 45°.

Computer contouring is, by its nature, an averaging process that is dependent on two factors: (1) the quality of the data input into the program and (2) the method used to calculate the contours. The quality of the input data is itself made up of several factors, including, but not limited to, (1) the number of control points used, (2) the distribution of the control points, (3) the number of stratigraphic units penetrated by each well, and (4) the accuracy of picks made by the investigator.

The detail shown by the isopach maps would have been greater if more logs had been used; however, budget and time constraints limited the data set to the selected subset of wells. Because of this, the maps and cross sections provide an overview of the geology of the basin rather than a detailed analysis of local areas. The area of salt anticlines, in the northeastern part of the basin, is especially complex, both structurally and stratigraphically.

The methods used for computer contouring vary according to the program used. In the ISM program used for this study, a grid is first constructed that is the basis for the contour lines. A grid defines a surface in three-dimensional space that is calculated from the input scattered-data (x, y, z) coordinates. The area shown on the maps was divided into a grid matrix of 300 rows and 300 columns. This is equivalent to a grid spacing in the x direction (longitude) of about 0.75 miles and a grid spacing of about 0.9 miles in the y direction (latitude).

Each grid node (intersection points between grid lines) is calculated in two steps: (1) initial estimation of grid node values and (2) biharmonic iterations using scattered-data feedback. The initial estimate is made by dividing the two-dimensional x, y space into octants centered on each grid node (Dynamic Graphics, Inc., 1988). Scattered-data points are selected within each octant depending on their distribution. Nearby points are used first within each octant, and the program will not search past two points in adjacent octants to calculate an empty octant; however, if no data are near a grid node, the program will search to the edge of the data set to find data. Once the points are selected, they are averaged using an inverse distance algorithm in which weighting is dependent on the angular distribution of the points.

After this initial estimate is made, ISM uses a biharmonic cubic spline function to fit a minimum tension surface to the grid nodes. To ensure that the minimum tension surface honors the scattered data as accurately as possible, a scattered-data feedback procedure is used to keep grid nodes tied to neighboring scattered data. In this study, as many as eight scattered-data points that fall within one-half cell of a grid node were used in this feedback procedure.

Once the minimum tension grid surface is calculated, ISM can use the grid to construct contour maps, cross sections, and perspective views of surfaces. It is essential to keep in mind that the final products are calculated from the grid values, not from the scattered data. Thus, there is some degree of averaging of the original data when constructing the contour maps.

The point of this discussion of techniques, and the relevance to the present study, is to illustrate that the contour maps presented herein were constructed using a consistent set of procedures that result in repeatable results. This method differs from hand-contouring methods because in the latter techniques the geologist commonly contours using a set of ill-defined and inconsistently applied procedures that introduce biases according to the individual's intent. This is not to say that a hand-contoured map is any less accurate than a computer-generated map. An individual's knowledge of an area is essential to the successful portrayal of a unit that is present in the subsurface and that is only known at scattered control points.

One of the shortcomings of computer-generated contour maps is that in areas of widely spaced control points, the importance of some data values may be exaggerated. For example, pinch-outs of units are not located precisely because of the distance between control points that define the pinch-outs. Rather than disregarding computer-generated maps as useless and going back to the "old-fashioned method of eyeballing," the limitations of computer maps need to be recognized and taken into consideration in any analysis of the data.

STRATIGRAPHY

In this report, the Cutler Group is considered to consist of the following lithostratigraphic units (fig. 3): (1) a lower Cutler unit that includes part of the Elephant Canyon Formation of Baars (1962), the "lower Cutler beds" of Loope and others (1990), the Rico Formation of some reports, and the Halgaito Formation, (2) the Cedar Mesa Sandstone, (3) the Organ Rock Formation, (4) the White Rim Sandstone, and (5) the De Chelly Sandstone. Where the Cutler cannot be subdivided, it is recognized as the Cutler Formation, undivided. The Permian Kaibab Limestone, also known locally as the Black Box Dolomite, overlies the Cutler on the far west side of the Paradox Basin and is discussed in the context of Permian stratigraphy and paleogeography. The names "Rico Formation" and "Elephant Canyon Formation" have been championed by some and vilified by others and are not used as formal rock-stratigraphic terms in this report. I discuss past usage of the units in this report and explain why I do not use them.

Figures 3*A*–3*D* are cross sections that show the stratigraphic relationships and nomenclature for the rock units discussed in this report. The cross sections were constructed by compiling data from the isopach maps of each stratigraphic unit along the lines of section. Exceptions are in areas of pinch-outs of units, such as the White Rim Sandstone or De Chelly Sandstone, where the isopach maps may exaggerate by a few miles the lateral extent of the units due to widely spaced control points.

Disputes over correlations of the Cutler in the Paradox Basin have been caused by: (1) the complexity of the Cutler depositional system and (2) an inconsistent use of stratigraphic names. In any given location, a vertical change in lithology is readily observable; in many instances, vertical interbedding between stratigraphic units can also be observed. Lateral facies changes are characteristic of almost all the units of the Cutler, and this has been especially troublesome in the study of basal Cutler strata. Although exposures along the Colorado River have aided study of the Cutler, a covered interval between the Hite, Utah, area and the Mexican Hat, Utah, area has led to correlation problems. There are also few outcrops of the Cutler in most of the eastern two-thirds of the basin, between the Colorado River and Monument upwarp on the west and the Uncompahgre Plateau and Needle Mountains on the east.

Disagreement about characteristics of the Hermosa and Cutler in the Paradox Basin has also led to divergent use of stratigraphic terms. One example is at Cane Creek anticline and Shafer dome in the northern part of the basin (fig. 2). McKnight (1940) stated that there are approximately 150–300 ft of Hermosa exposed, which are overlain by 585 ft of Rico Formation. Conversely, Baars (1971) did not recognize any Hermosa at those localities and assigned the whole succession to the Elephant Canyon Formation. Another example is in the southern part of the basin along the San Juan River. Baker (1936) picked the contact between the Hermosa and the Rico at a change from massive limestones below to thinner limestones and red beds above, but O'Sullivan (1965) picked the contact approximately 100 ft higher in the section on other lithologic criteria. Baars (1962) assigned the entire section to the Hermosa. These are but two examples of people using different names for the same strata; similar examples could be cited for many other places in the basin. The converse, using the same name for different strata without explicitly saying so, has also been done and has led to miscorrelations and confusion.

UNDERLYING ROCKS

HONAKER TRAIL FORMATION

In most of the Paradox Basin, the Pennsylvanian Honaker Trail Formation of the Hermosa Group, or the Hermosa Formation, undivided, underlies the Cutler Group. The exceptions are along the northeastern margin of the basin where the Cutler overlies Proterozoic rocks and west of the basin, on the San Rafael Swell, where the Cutler locally overlies Mississippian rocks. The datum used in this report for the top of the Honaker Trail in the subsurface was generally that picked on AMSTRAT logs or by Rocky Mountain Geological Databases, Inc. (RMGD). The upper part of the Honaker Trail is characterized by thick limestone beds associated with varying amounts of sandstone and shale. The amount and composition of interbedded sandstones changes from place to place in the Paradox Basin, depending on the distance from the Uncompahgre highlands and the environments of deposition in which the sandstones were deposited.

It is unlikely that there is a single limestone that extends throughout the basin that could be used as a datum for the top of the Honaker Trail. Limestones have been observed to thin, grade into sandstone and shale, or otherwise change facies laterally in some exposures. Atchley and Loope (1993) showed that depositional cycles in the Honaker Trail along the southwestern basin margin cannot be traced to the north. The limited control points in some areas of the basin make it impossible to accurately trace individual limestone beds from one well to another. There is usually a marked lithologic break at the top of the Honaker Trail, however, and that is the basis for the pick between the Hermosa and Cutler. Examples of this pick are shown on figure 4.

Reports by Dane (1935), Cater (1970), Franczyk (1992), and Franczyk and others (1995) summarized the lithology of the upper part of the Hermosa along the northeast margin of the basin, the areas closest to the Uncompahgre highlands. Limestone beds are gray to yellowish gray, dense, medium to thick bedded, and fossiliferous. Common fossils are brachiopods, pelecypods, echinoids, corals, gastropods, and fusilinids. Chert concretions are present in some limestone beds. In general, sandstone beds of the upper Hermosa in this area are gray, yellowish gray, and tan; conglomeratic to fine grained; subarkosic to arkosic; and thick bedded. The shale beds in the upper Hermosa are generally gray, green, and tan, as opposed to red shale beds in the Cutler, and are evenly bedded. Neither Dane (1935) nor Franczyk (1992) and Franczyk and others (1995) recognized strata that could be assigned to the Rico Formation, and Cater (1970) could not identify a Rico Formation in most of his study area. The Cutler overlies the Hermosa or Proterozoic rocks in the areas discussed by those authors. Farther southwest in the Paradox Basin, the lithology of the Honaker Trail changes somewhat. It has been described in those areas by Baker (1933, 1936, 1946), McKnight (1940), Wengerd and Matheny (1958), Lewis and Campbell (1965), O'Sullivan (1965), Melton (1972), Loope (1984, 1985), Loope and others (1990), Sanderson and Verville (1990), and Atchley and Loope (1993) among others.

From Cane Creek anticline to the confluence of the Green and Colorado Rivers (hereafter called the

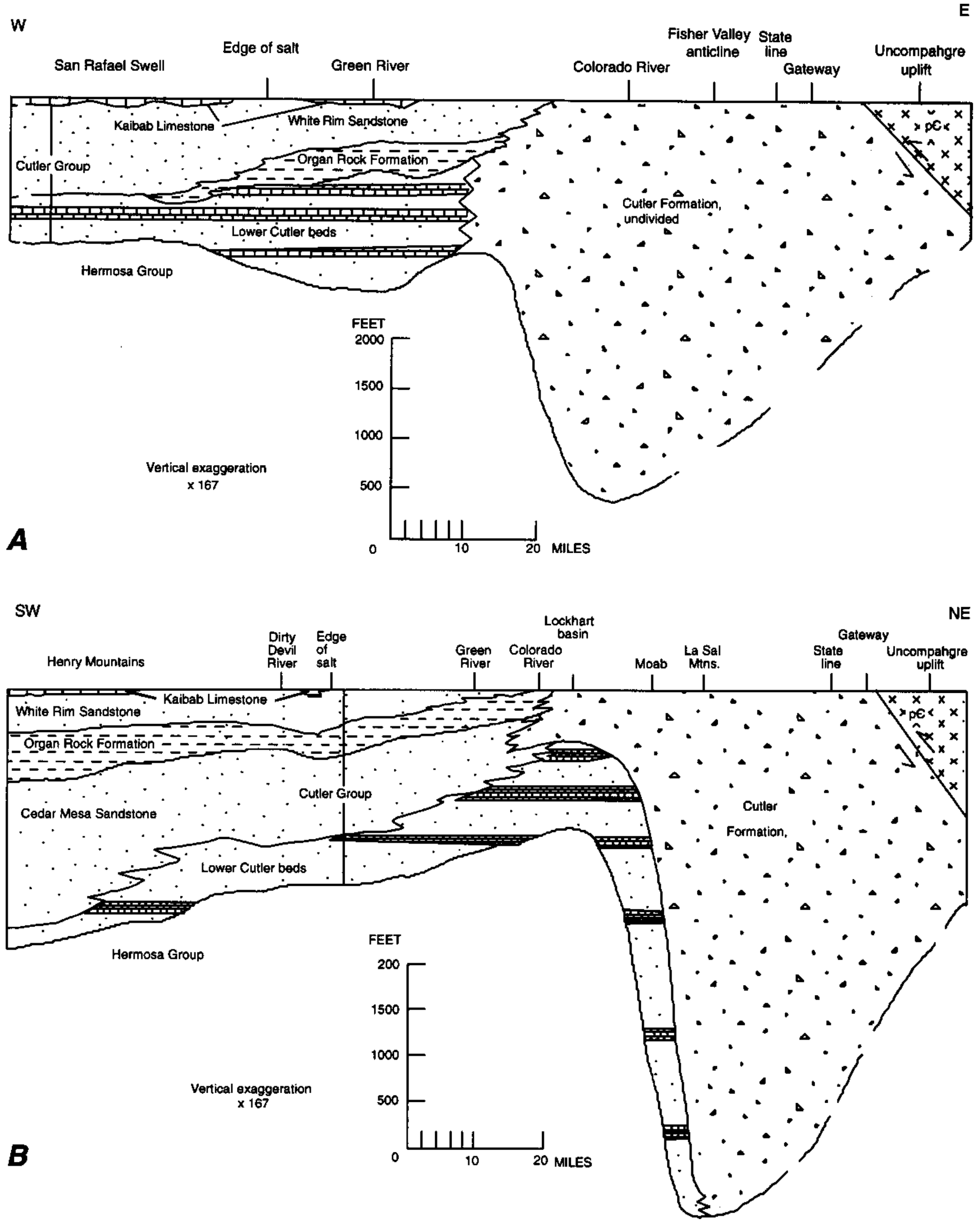
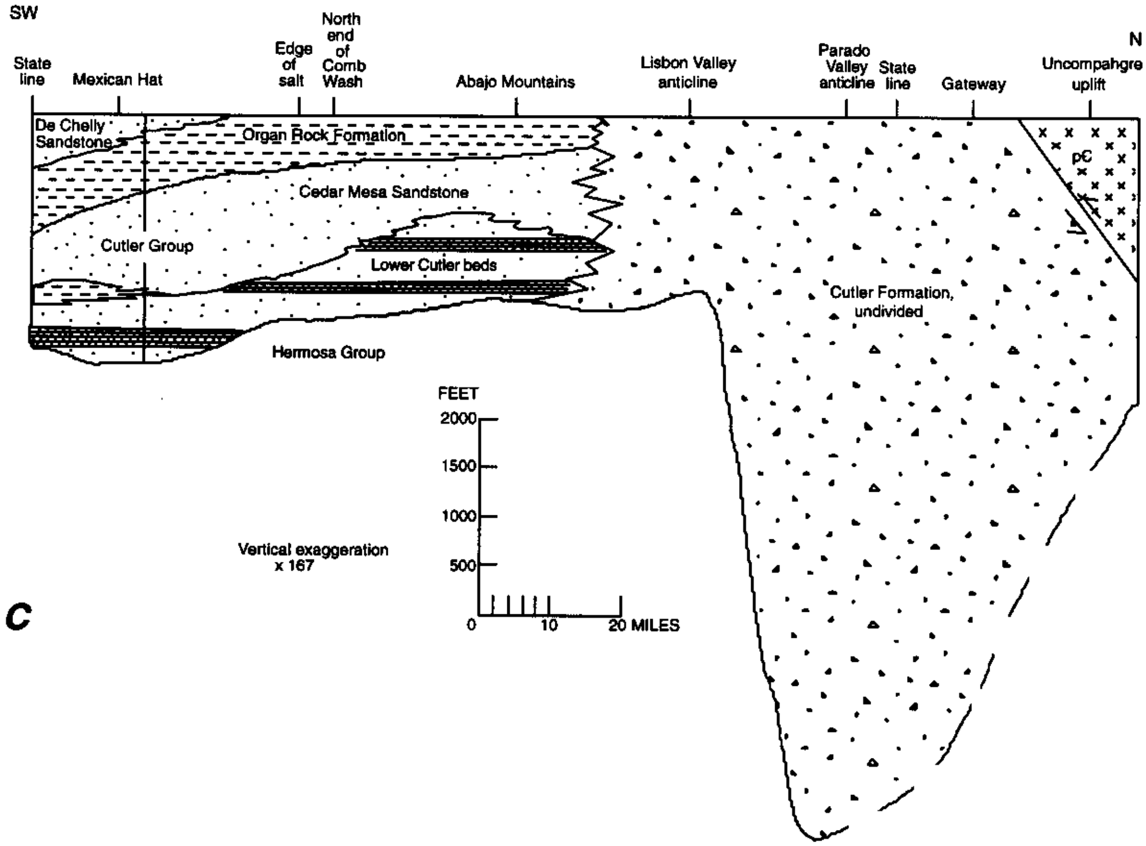


Figure 3 (above and facing page). Cross sections showing stratigraphic relationships and nomenclature used in the Paradox Basin. Locations of the cross sections are shown on plate 1. Datum is the basal Triassic unconformity. Cross sections were constructed by compiling thickness data from isopach maps along indicated lines of section. The number and position of limestone beds in the lower Cutler beds is schematic. *A,* Uncompahgre uplift to San Rafael Swell; *B,* Uncompahgre uplift to Henry Basin; *C,* Uncompahgre uplift to Monument upwarp; *D,* Uncompahgre uplift to San Juan Basin.


SW
N
State line
Mexican Hat
Edge of salt
North end of Comb Wash
Abajo Mountains
Lisbon Valley anticline
Parado Valley anticline
State line
Gateway
Uncompahgre uplift
De Chelly Sandstone
Organ Rock Formation
Cedar Mesa Sandstone
Cutler Group
Lower Cutler beds
Cutler Formation, undivided
Hermosa Group
pC
FEET
2000
1500
1000
500
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10
20 MILES
Vertical exaggeration x 167
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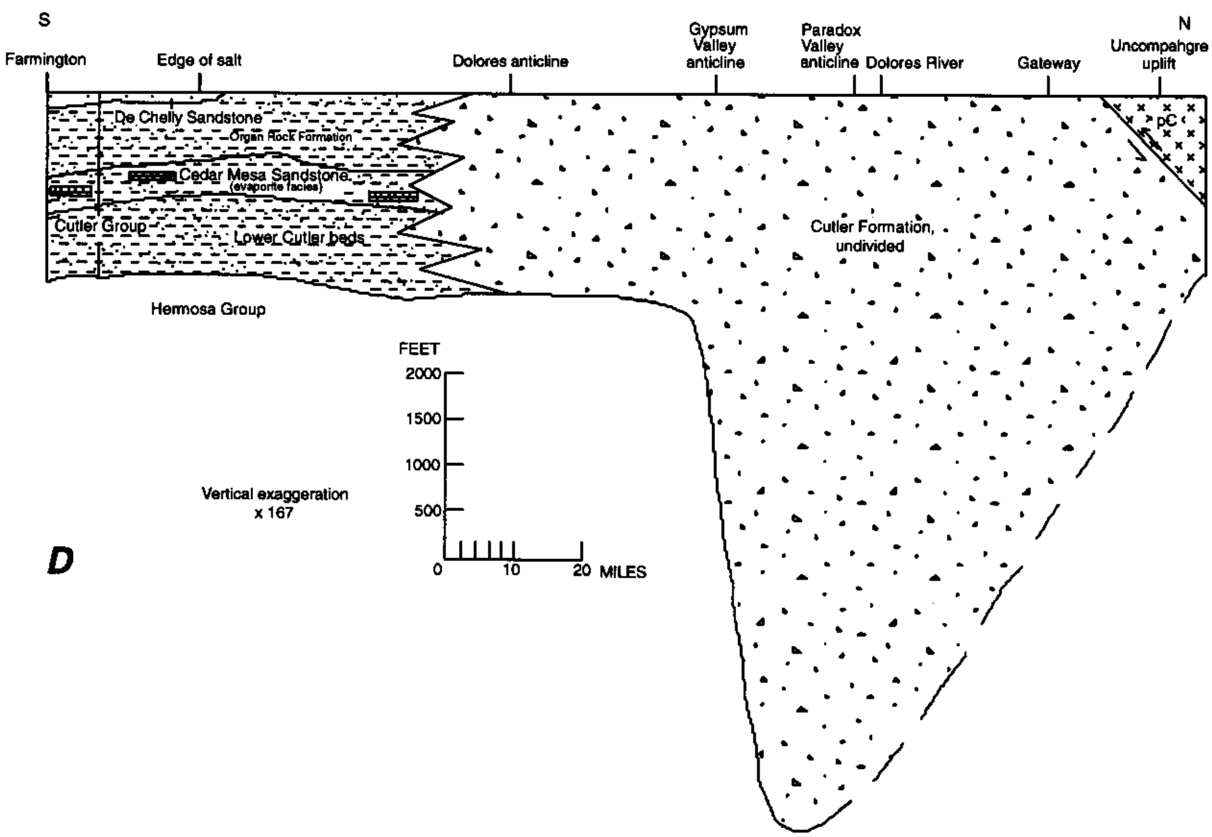
S
N
Farmington
Edge of salt
Dolores anticline
Gypsum Valley anticline
Paradox Valley anticline
Dolores River
Gateway
Uncompahgre uplift
De Chelly Sandstone
Organ Rock Formation
Cedar Mesa Sandstone
(evaporite facies)
Cutler Group
Lower Cutler beds
Cutler Formation, undivided
Hermosa Group
pC
FEET
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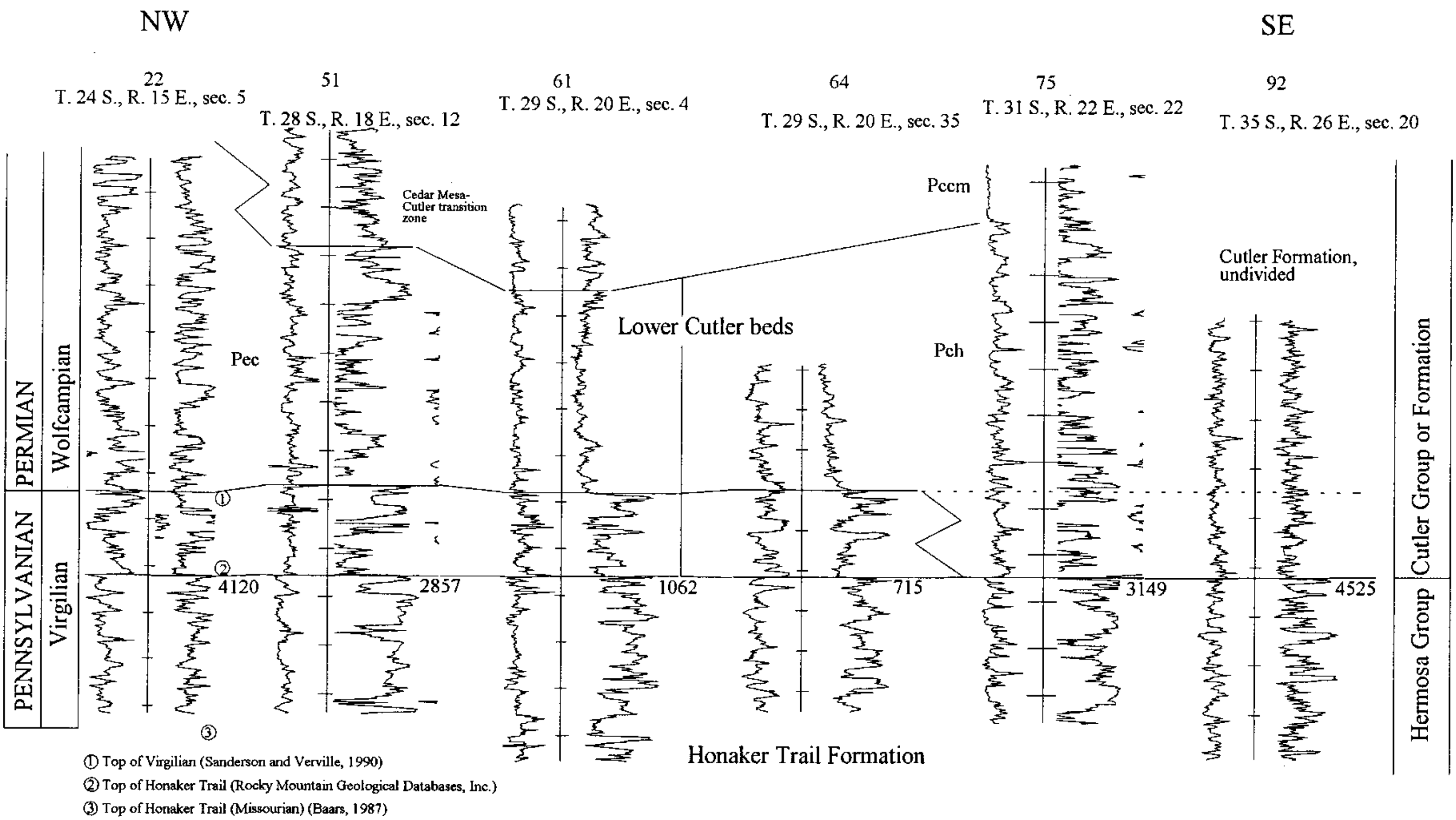

Figure 4. Cross section showing well logs of section at the Pennsylvanian-Permian boundary from near the San Rafael Swell to the Utah-Colorado State line. Location of cross section is shown on plate 1. Numbers above well logs correspond to those on plate 1 and in Appendix 1. All logs are gamma ray-neutron. Uppermost Virgilian limestones pinch out laterally into red beds of typical Cutler lithology. Pccm, Cedar Mesa Sandstone; Pch, Halgaito Formation; Pec, Elephant Canyon Formation. The numbers at the top of the Honaker Trail Formation are picks from the Rocky Mountain Geological Databases, Inc., database.

Confluence), the Honaker Trail is composed of thick beds of sandstone, limestone, and shale. McKnight (1940, p. 22) reported that sandstone and arkose make up 49 percent of the formation, limestone 31 percent, and shale 20 percent at a location on the Colorado River just upstream from the Confluence. Sandstone beds are as thick as 75 ft, limestone beds are as thick as 40 ft, and shale beds are as thick as 20 ft. Sandstone is white, gray, greenish, or reddish; fine to medium grained; and commonly cross-bedded. Limestone is gray, dense, fossiliferous, and contains chert nodules in some beds. Shale is mainly gray to green, although some beds are reddish. Shale beds are commonly calcareous and contain marine fossils in some places.

Some of the best exposures of the Honaker Trail Formation are along the Colorado River just south of the Confluence (Baker, 1946). In this area, the Honaker Trail is composed mainly of interbedded limestone and sandstone in nearly equal amounts and a small percentage of shale. Limestone occurs in beds as thick as about 45 ft and is light to dark gray, dense, cherty, and fossiliferous. Sandstone is in beds as thick as about 50 ft and is light to dark gray, greenish gray, tan, and salmon; fine to medium grained; and cross-bedded. Loope (1984, 1985) interpreted the sandstones in the upper part of the Honaker Trail Formation in this area as eolian in origin. The sandstones have medium- to large-scale cross-beds and transport directions to the southeast (Loope, 1984). Atchley and Loope (1993) indicated that eolian sandstones make up about 50 percent or more of the Honaker Trail from the Confluence area southward to Elk Ridge.

Honaker Trail exposures near Elk Ridge were described by Lewis and Campbell (1965). In that area, the interbedded lithologies of limestone, sandstone, and shale persist. Limestone beds are gray, dense, cherty, fossiliferous, and are as thick as 60 ft. Sandstone beds are commonly light gray, calcareous, and as thick as 30 ft. Shale beds are gray, thin bedded, calcareous, and as thick as 15 ft. Lewis and Campbell (1965, p. B8) noted that the upper Hermosa is gray and the overlying Rico Formation is red, although Murphy (1987) described red siltstone in the upper Hermosa at Dark Canyon.

The southernmost exposures of the Honaker Trail are in the canyon of the San Juan River, near Mexican Hat, Utah (fig. 1). This area has been described by Woodruff (1912), Miser (1925), Baker (1936), Wengerd and Matheny (1958), Wengerd (1963, 1973), O'Sullivan (1965), and Goldhammer and others (1991). Access to the Hermosa is relatively easy in this area because a trail leads from the rim of the canyon down to the San Juan River. Although this is the type area for the Honaker Trail Formation (Wengerd and Matheny, 1958), some have argued that the name should not have been applied here (Hite and Buckner, 1981). Evaporite rocks of the underlying Paradox Formation pinch out before reaching Honaker Trail, so the basal contact of the Honaker Trail Formation is arbitrary at this locality.

In contrast to areas north of Elk Ridge, the Honaker Trail Formation along the San Juan River has relatively little sandstone and proportionately more limestone and shale. In a section on the San Juan River, H.D. Miser measured 840.5 ft of the Honaker Trail (Baker, 1936). Of this thickness, less than 5 percent is sandstone, 55 percent is limestone, and 40 percent is shale or covered interval. As in areas to the north, limestone beds here are thick, gray, massive, cherty, and fossiliferous. Shale beds are also thick and are mainly gray and calcareous. The few sandstone beds are gray to yellow, calcareous, fine grained, and cross-bedded. Baker (1936) noted that, although the contact of the Hermosa with the overlying Rico is gradational, the massive, somber-colored limestone and sandstone of the Hermosa contrasts strongly with the thin-bedded, reddish-colored rocks of the Rico.

RICO FORMATION AND ELEPHANT CANYON FORMATION

The term "Rico Formation" originated with Cross and Spencer (1900) for exposures near Rico, Colo. (fig. 1). The Rico was envisioned as a unit transitional between the Hermosa, below, and the Cutler (at that time considered part of the Dolores Formation), above. As such, it contained both marine limestones and continental clastic red beds. A faunal change from dominantly brachiopods in the Hermosa to dominantly pelecypods in the Rico was used as a distinguishing criterion. The upper contact of the Rico was vaguely defined as being the highest occurrence of Rico fossils; the Cutler is unfossiliferous. The Rico was considered Permian(?) in age by Cross and Howe (1905).

The term "Rico Formation" was first used in southeastern Utah by Prommel (1923), who was then followed by Baker and others (1927). Baker and Reeside (1929) correlated the Rico throughout the Paradox Basin, and the term became commonly used in the region through the reports of Baker (1933, 1936, 1946) and McKnight (1940). In all of these reports, the Rico was considered to be Permian in age, determined on the basis of marine fossils, and was thought to represent beds transitional between the Hermosa and Cutler.

Baars (1962) vigorously objected to the concept of a transitional unit between the Hermosa and the Cutler. His objections were mainly based on (1) an interpreted unconformity between the Hermosa and Cutler in much of the region and (2) the fact that beds assigned to the Rico are time transgressive, becoming younger to the west. In its place, Baars (1962) introduced the name "Elephant Canyon Formation," which was defined as the sequence of Permian (Wolfcampian) carbonates present only in the northwestern part of the Paradox Basin. Key points in the definition of the Elephant Canyon are (1) that it overlies the Systemic boundary between the Pennsylvanian and the Permian and (2) this boundary was interpreted as an unconformity. As thus defined, the Elephant Canyon was a chronostratigraphic unit, not a lithostratigraphic unit, because rocks of the underlying Hermosa Group have a lithology similar to that of the lower part of the Elephant Canyon.

Although Baars' (1962) intent was to simplify the nomenclature and refine paleogeographic interpretations, many reports continued to use a mix of the terms "Rico Formation" and "Elephant Canyon Formation." For example Wengerd (1973, p. 134) showed both units as present, with the Elephant Canyon overlying the Rico; Molenaar (1975, p. 142) only showed the Elephant Canyon; Campbell (1979, p. 15) used both terms interchangeably; Loope (1984) used only the Rico Formation; and Campbell (1987, p. 93) used only the Elephant Canyon Formation.

There is some indication that the Elephant Canyon was used in ways other than how Baars (1962) had defined it. For instance, a geologic map of Canyonlands National Park, including the type area for the Elephant Canyon, shows 300–400 ft of Honaker Trail Formation underlying the Elephant Canyon near the mouth of Elephant Creek (Huntoon and others, 1982). Baars' original definition of the unit (Baars 1962, p. 176) stated that only 55 ft of Honaker Trail Formation is exposed above river level at that locality. Huntoon and others (1982) showed about 400–500 ft of Elephant Canyon at the Confluence, whereas Baars (1975) stated that there is about 1,000 ft of Elephant Canyon there.

Loope (1984), Loope and others (1990), and Sanderson and Verville (1990) asserted that they could find no evidence of an unconformity at the base of Baars' (1962) Elephant Canyon and thus disputed the concept of the Elephant Canyon Formation. Initially, Loope (1984) reverted to the nomenclature of McKnight (1940) and Baker (1946) by using the term "Rico Formation" for strata between the Hermosa and Cutler. Eventually, Loope and others (1990) acknowledged that the term "Rico Formation" might be inappropriate and used an interim name "lower Cutler beds" for that interval. Field checking of these strata by A.C. Huffman, Jr. and me in nearby Big Springs Canyon revealed that the base of Loope and others' (1990) lower Cutler beds corresponds to the base of the Elephant Canyon as mapped by Huntoon and others (1982).

Condon (1992), Huffman and Condon (1993), and Condon and Huffman (1994) recognized the Rico Formation in the San Juan Basin. The unit had been previously identified as such by Wengerd and Matheny (1958) and can be traced through much of the basin in the subsurface. In comparing the southeast end of figure 4 (of this report) and cross section F-F′ of Condon and Huffman (1994), it is apparent that the top of our Rico Formation in the San Juan Basin corresponds to the top of the Honaker Trail Formation as recognized here in the Paradox Basin. On the basis of the correlations presented herein, it now seems that the unit recognized as Rico in the San Juan Basin underlies the Rico of the Mexican Hat, Confluence, and Shafer dome areas of southeastern Utah. The Rico, as recognized by Huffman and Condon (1993) in the San Juan Basin, is probably entirely Pennsylvanian in age.

Because of the varied past usage of the term "Rico Formation" and the disputed status of the Elephant Canyon Formation, I use neither term as a formal name in this report. I continue to use the term "lower Cutler beds" in the sense of Loope and others (1990). As defined, it is a lithostratigraphic unit lying above the Hermosa Group and below or adjacent to the Cedar Mesa Sandstone. As demonstrated below, this unit consists partially of the Elephant Canyon Formation of Baars (1962), the "Rico Formation" of some authors, and the Halgaito Formation, depending on the location in the basin. The lower Cutler beds, as used by me, includes both Pennsylvanian and Permian strata, based on fusilinid identifications presented in Loope and others (1990) and Sanderson and Verville (1990).

CUTLER GROUP

CUTLER FORMATION, UNDIVIDED

Along the southwestern margin of the Uncompahgre plateau, the Cutler is not divided into members or formations. It consists of a heterogeneous sequence of arkosic conglomerate and lesser amounts of arkosic sandstone, siltstone, and mudstone. Detailed stratigraphic and sedimentological studies of the Cutler in the northeastern part of the Paradox Basin include those by Baker (1933), Dane (1935), McKnight (1940), Baars (1962), Cater (1970), Rascoe and Baars (1972), Werner (1974), Mack (1977), Campbell (1979, 1980, 1981), Campbell and Steele-Mallory (1979), and Mack and Rasmussen (1984). Paleontological studies were summarized by Lewis and Vaughn (1965) and Baird (1965).

As a whole, the formation is dark red, purple, and maroon, although some beds are gray to greenish. Conglomerates are poorly sorted; material ranges from sand size to boulders as large as 25 ft (Schultz, 1984). Trough cross-bedding and horizontal bedding are present in some of the sandstone beds, and ripple marks are present in some of the finer grained rocks. There are few sedimentary structures in the coarsest conglomerates, but clasts are graded both normally and inversely, and some pebbles display imbrication dipping to the northeast. Pebbles, cobbles, and boulders within the Cutler are derived from nearby Proterozoic rocks (Werner, 1974). In the Gateway, Colo., area, debris flow and proximal-braided-stream deposits have been described (Campbell, 1980; Mack and Rasmussen, 1984; Schultz, 1984). This area and two others along the Uncompahgre front were interpreted as alluvial fans (Campbell, 1980).

Clastics of the Cutler Formation, undivided, become finer grained southward and westward from the Uncompahgre front (Baker, 1933; Dane, 1935; Cater, 1970). Campbell (1979, 1980) interpreted this as a change from a proximal braided facies in the northeast to meandering stream systems farther to the southwest within an alluvial fan depositional system. In the central and southwestern parts of the Paradox Basin, the Cutler can be divided into individual formations within the Cutler Group (Baars, 1962). Baker (1933, 1946), McKnight (1940), Langford and Chan (1988, 1989), and Stanesco and Campbell (1989) described the gradation of the undivided Cutler into the Cutler Group. The gradation does not occur along a sharp boundary but rather occurs over a distance of many miles. Figure 5 shows the Cutler Formation along Indian Creek, east of the Confluence, which is in the zone of gradation. Various plates in this report show the areas over which the constituent formations of the Cutler Group can be recognized.

Plate 3 is an isopach map showing the general thickness of the Cutler Formation or Group in the Paradox Basin. The range in thicknesses used for this map is from 0 to 8,165 ft, although Baars (1975) mentioned that at least 15,000 ft of Cutler had been drilled in the basin in one well. Figures 3*A*–3*D* show a direct correspondence between the fold and fault belt and deposition of the Cutler. Within the salt anticline region, the Cutler is undivided and consists of alluvial, arkosic rocks. Outside this area, the Cutler can be divided into formations on the basis of lithology and depositional environments. The salt anticline area seems to have acted as a trapping mechanism for fluvial sediments being shed from the Uncompahgre highlands. The true distribution of thick and thin areas is much more complex than can be shown here because of widely spaced control points. Rising salt anticlines caused the Cutler to both thicken markedly in the adjacent synclines and to thin over the tops of the anticlines. In some places within the fold and fault belt, the Cutler is absent on the tops of some anticlines. Cross sections in Cater (1970) show the thickness variations of the Cutler in the Paradox Valley area.

LOWER CUTLER BEDS

CONTACTS

Basal arkoses of the Cutler Formation become finer grained to the southwest of the Uncompahgre Plateau and eventually merge into units that have been called Rico Formation, Elephant Canyon Formation, lower Cutler beds, or Halgaito Formation in different parts of the basin or by different geologists. This interval has been the subject of more debate concerning correlations than any other unit in the Cutler, so the bottom and top contacts, as used in this report, need to be clearly defined.

In the Cane Creek anticline and Shafer dome areas in the northern part of the basin, I pick the top of the Hermosa at the same horizon as McKnight (1940) and Lohman (1974, p. 52), which is at the top of massive white to gray limestone and sandstone beds (fig. 6). The interbedded limestone, sandstone, and reddish mudstone beds above the Hermosa have been previously assigned to the Rico (McKnight, 1940) or to the Elephant Canyon (Baars, 1971). The top of the lower Cutler beds is at the top of the Shafer limestone,[1] which forms a bench on either side of the river in this area.

The contact I recognize between the Hermosa and lower Cutler at the confluence of the Green and Colorado Rivers (fig. 7) is the same as McKnight (1940) and Loope and others (1990). The pick is at the change from massive gray and white limestone and sandstone beds to red hues of the lower Cutler. There is an increase in arkosic beds in the lower Cutler and a decrease in the amount of limestone in this area. The top of the lower Cutler beds is at the base of the overlying Cedar Mesa Sandstone. Baars (1962) placed all but the lower 55 ft of strata between the river and the Cedar Mesa in the Elephant Canyon. McKnight (1940) considered the lower Cutler beds to be the Rico Formation.

The stratigraphic relationships observed at the Confluence continue southward through outcrops exposed along the Colorado River. I observed these outcrops by raft through Cataract Canyon and from the canyon rim at Gypsum Canyon and Dark Canyon (fig. 1). At Gypsum Canyon, limestone beds of the lower Cutler beds are interbedded with sandstone of the overlying Cedar Mesa Sandstone. This interbedding at the outcrop is also evident in many of the well logs in the area.

Between Dark Canyon and Mexican Hat, Utah, there is a gap in outcrops of the strata underlying the Cedar Mesa Sandstone of nearly 50 mi. A well approximately half way between those areas shows the log characteristics of this interval (fig. 8). The logs shown in figure 4 also show the character of the lower Cutler in the subsurface of the basin.

In the canyon of the San Juan River, I agree with Baker (1936) in placing the top of the Hermosa at the top of the massive limestone and sandstone sequence. Overlying thinner bedded strata, which contain reddish sandstone and siltstone in addition to minor limestone, are included in the lower Cutler beds. The lower Cutler includes all strata to the base of the Cedar Mesa Sandstone in this area (fig. 9), which includes beds previously assigned to the Rico and Halgaito Formations

LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS

In most of the basin, strata above the Hermosa and below the Cedar Mesa Sandstone or equivalent rocks are

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[1] The Shafer limestone is not a formal stratigraphic unit recognized by the U.S. Geological Survey. Its name was attributed by McKnight (1940) to H.W.C. Prommel, a geologist who was active in stratigraphic and structural studies in the Moab area in the 1920's. The name was used by Prommel and Crum (1927) and was subsequently used by the U.S. Geological Survey in various Bulletins concerned with this area. The Shafer was used by McKnight (1940) as a marker bed for the top of the Rico Formation in the area he mapped between the Green and Colorado Rivers. The Shafer is noteworthy today because the northeastern access roads leading into Canyonlands National Park are built on this resistant unit.

Figure 5. Undivided Cutler Formation at Indian Creek, east of the confluence of the Green and Colorado Rivers; person for scale in center of photo. In this area, Cutler fluvial strata are interbedded with eolian strata. Purple fluvial strata are composed of coarse-grained channel arkose and mudstone overbank material. This facies forms the lower part of the massive cliff just above the road. Orange eolian strata are finer grained and form the middle part of these cliffs. Some eolian strata have been bioturbated and are massive, but high-angle cross-beds are visible in some beds.

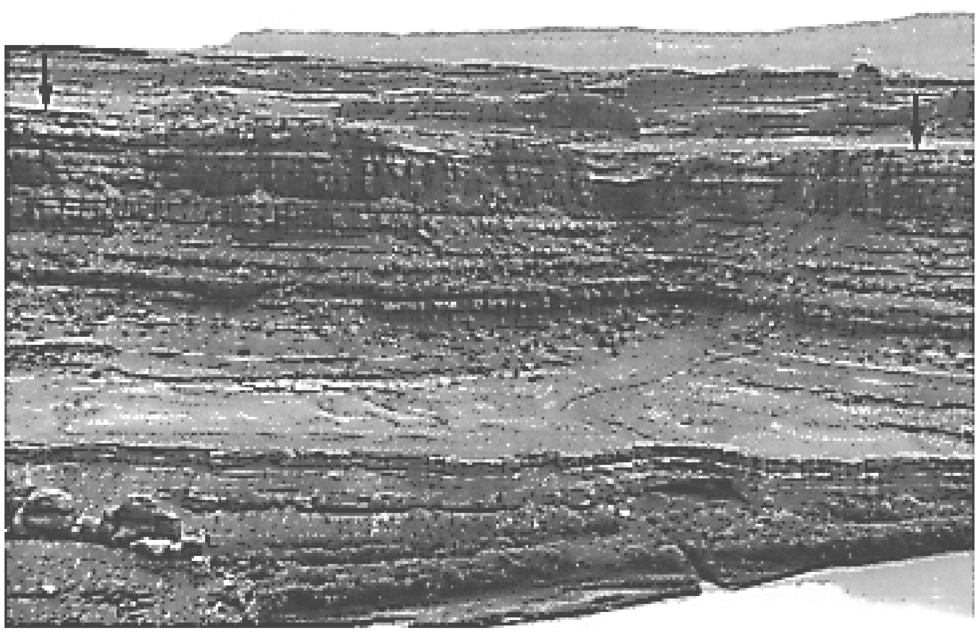

Figure 6. Honaker Trail Formation, lower Cutler beds, and upper part of Cutler Formation at Shafer dome. Top of Honaker Trail is at top of bench above Colorado River. Top of lower Cutler beds is at top of Shafer limestone (arrows). Interbedded fluvial and eolian strata of the Cutler Formation form cliff above the lower Cutler beds. Mesozoic units form cliff in the background. Thickness of lower Cutler beds here is approximately 580 ft.

Figure 7. Honaker Trail Formation, lower Cutler beds, and Cedar Mesa Sandstone at the confluence of the Green and Colorado Rivers. View is to the north; Green River is on the left flowing toward viewer. Contact between the Honaker Trail and the lower Cutler is marked by change from gray and white beds to red beds (arrow). Cedar Mesa Sandstone forms the cliffs at the top of the exposure. Lower Cutler beds are approximately 600 ft thick here.

a mix of quartzose sandstone and arkose, minor conglomerate, mudstone, siltstone, and limestone (fig. 4). This package grades northwestward into a carbonate-dominated succession that overlies the Hermosa and underlies the Organ Rock Formation or White Rim Sandstone (fig. 3*A*). Plate 4 shows the distribution and thickness of these beds as recognized in this report.

Outcrops of the lower Cutler beds in the Cane Creek anticline and Shafer dome areas in the north-central part of the basin are dominated by quartz sandstone and arkose. Sandstone beds are dark red, orange, and pinkish to light greenish gray, fine to coarse grained, and cross-bedded. Many of the sandstone beds have been interpreted as eolian deposits (Terrell, 1972). Arkose is dark red, maroon, and purple, fine to coarse grained, cross-bedded, and contains pebbles and cobbles at the base of some beds. Arkose beds commonly display scour-and-fill structures and have erosive bases. Terrell (1972) noted a 60-ft conifer log in an arkose channel at Cane Creek anticline; similar petrified wood is present in the core of Shafer dome (fig. 10). The coarse grain size, sedimentary structures, and association with channels indicates deposition of the arkose in fluvial channels and related environments. Red, brown, and green siltstone or mudstone is also commonly interbedded with sandstone or arkose.

Limestone beds are gray, cherty, and fossiliferous. Limestone beds are most abundant near the top and base of the interval, and the middle part is dominated by quartz sandstone and arkose. The Shafer limestone at the top of the lower Cutler beds forms a broad bench over much of this area, but pinches out on the northeastern flank of Cane Creek anticline.

Terrell (1972) interpreted the beds of the lower Cutler in the north-central part of the basin as deposits of a delta system in an arid region. His model consisted of fluvial channels draining the Uncompahgre highlands to the northeast and flowing southwestward through eolian dune fields to an open-marine sea. The interbedding of arkose, sandstone, and limestone were interpreted to represent the complex shifting of fluvial channels, dune fields, and delta lobes across the area. This interpretation was supported by Tidwell (1988), who discovered a thin coal seam and a flora representative of swampy conditions in this same area.

From the Confluence to Dark Canyon, the lower Cutler beds are characterized by the same mix of quartz sandstone, arkose, and limestone that is present at Cane Creek anticline and Shafer dome (Baker, 1946; Lewis and Campbell, 1965; Loope, 1984). Loope (1984) pointed out that much of the sandstone in the lower Cutler is fine to medium grained and cross-bedded in medium- to large-scale sets. The transport direction of these sandstones was to the southeast. Loope (1984) interpreted these sandstone beds as eolian in origin. Other sandstone beds are flat-bedded, fine to coarse grained, and contain vertebrate trackways in places (Loope, 1984).

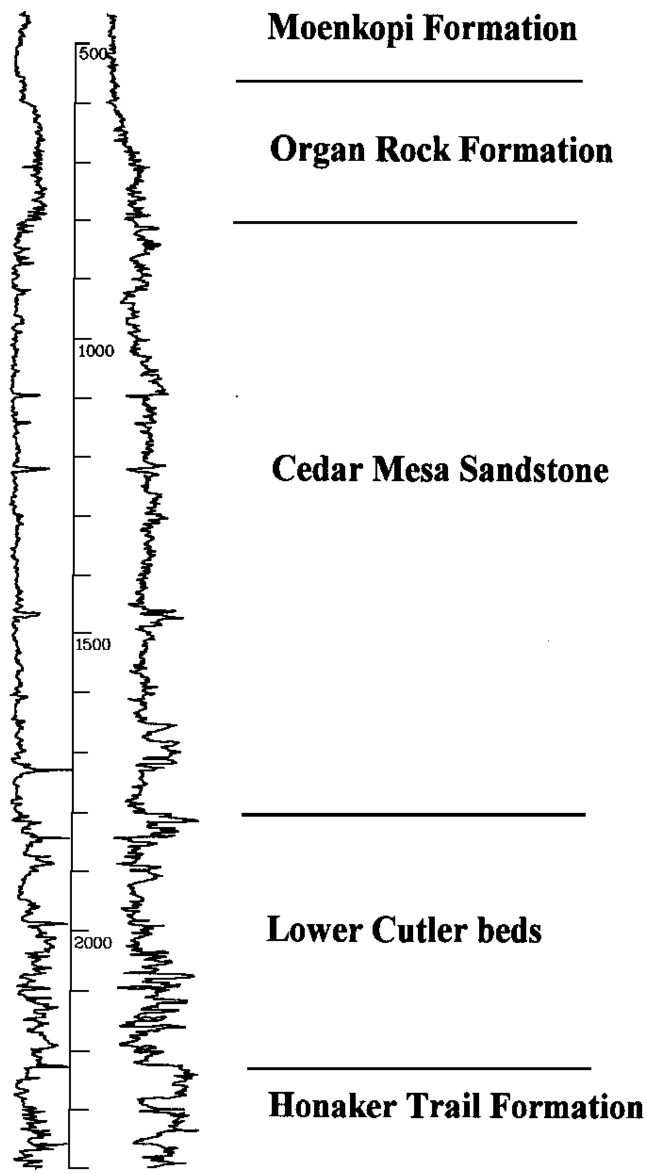

Figure 8. Well log showing the lower part of the Moenkopi Formation, Organ Rock Formation, Cedar Mesa Sandstone, lower Cutler beds, and the upper part of the Honaker Trail Formation at Elk Ridge. Well is number 94 (plate 1 and Appendix 1). Log curves are gamma ray on the left and interval transit time on the right. Note the blocky nature of the Cedar Mesa Sandstone that contrasts with interbedded limestone, mudstone, and sandstone of the lower Cutler beds. Massive limestone and sandstone beds mark the top of the Honaker Trail. Vertical scale is in feet.

Kocurek and Nielson (1986) interpreted these strata as eolian sand sheets. Arkose beds in the Cataract Canyon area are generally confined to the lower part of the section (Baker, 1946; Loope, 1984) and are finer grained than correlative beds to the northeast in the Moab area. These arkose beds seem to indicate renewed uplift of the Uncompahgre highland, possibly accompanied by a wetter climate and a resulting pulse of arkosic sediment into the basin. Limestones are both gray, thick bedded, cherty, and fossiliferous and thin bedded and sandy to argillaceous. Limestones are again concentrated at the top and base of the lower Cutler in this area; the middle part is mainly red beds. A limestone bed at the top of the interval, northeast of the Confluence, was observed to be cross-bedded. This, or a similar bed, was interpreted as a migrating sand wave (Loope, 1984) or a tidal channel (Kocurek and Nielson, 1986). One limestone bed at the top of the lower Cutler beds pinches out to the northeast in outcrops along the Colorado River (McKnight, 1940). Other limestones appear higher in the section northwestward from the Confluence area (fig. 4). Mudstone and siltstone beds are present, but poorly exposed, in the lower Cutler beds. Desiccation cracks, adhesion ripples, possible paleosols, and leaf fragments in mudstone and siltstone beds suggest deposition in lacustrine or tidal-flat environments (Loope, 1984; Kocurek and Nielson, 1986).

In the San Juan River canyon, the lower Cutler beds (previously included in the Rico Formation) consist of silty sandstone and siltstone interbedded with limestone and mudstone. Sandstone is white, gray, and red, silty, very fine grained, and cross-bedded. Siltstone is reddish brown, calcareous, and slope forming. The siltstone gives this part of the section its characteristic reddish hue. O'Sullivan (1965) noted that the siltstone beds are very similar to those in overlying strata he mapped as the Halgaito Formation. Limestone beds are gray to brown, sandy, fossiliferous, and form laterally persistent ledges along the canyon walls (fig. 9). Some of the sandstone beds are also calcareous and form ledges similar to the limestone beds.

This part of the section consists of several progradational-transgressive cycles in which continental red beds are sharply overlain by transgressive marine limestones. The lateral continuity of strata, general lack of channel deposits, and homogeneity of the red bed units indicates deposition in a low-relief area near the sea but not in an area influenced by prograding delta lobes. Murphy (1987) interpreted the red siltstones of this interval as loess deposits.

At the surface in the San Juan River area, the upper part of the lower Cutler beds (previously included in the Halgaito Formation) is brick red and consists mainly of interbedded very fine grained silty sandstone and sandy siltstone. Some sandier or more calcareous beds weather to ledges, but as a whole the unit forms a slope below the Cedar Mesa Sandstone (fig. 9). A few thin, gray, nodular limestone beds that pinch and swell along strike are present near the base of the unit. Some thin fluvial channels contain limestone pebble conglomerates, and paleosols are present throughout the section. Vaughn (1973) summarized the vertebrate fauna in these strata and stated that the vertebrate fossils are confined to stream-channel deposits. The fauna includes abundant fresh-water sharks, rhipidistian crossopterygian fish, actinopterygian fish, lungfish, amphibians, and primitive

Figure 9. Honaker Trail Formation, lower Cutler beds, and Cedar Mesa Sandstone at Johns Canyon, west of Mexican Hat, Utah. Top of Honaker Trail forms the lower ledges at the base of the exposure. Top of Rico Formation is at top of double ledge in center of photograph. Halgaito Formation forms slope at base of Cedar Mesa cliffs in background and is about 465 ft thick here. Cedar Mesa is of variable thickness due to erosion but averages about 700 ft in this area.

Figure 10. Stump of petrified wood from lower Cutler beds near the Colorado River in the center of Shafer dome; Brunton compass in center of photograph for scale. Other wood is encased in arkosic channel sandstone bed in background. Channel sandstone is just above contact with the Honaker Trail Formation. Terrell (1972) described a similar “conifer” log from the nearby Cane Creek anticline in beds at the same stratigraphic position.

reptiles. The flora of this interval includes *Calamites*, arborescent lycopods, and seed ferns (Vaughn, 1973).

Gregory (1938, p. 41) noted the similarity of the strata previously mapped as Rico and Halgaito and stated, “Except for the fossils and the larger numbers of persistent limestone beds in the Rico there is little to distinguish that formation from the overlying Cutler. Both are Permian red beds, both are dominantly calcareous, irregularly bedded, more or less arkosic sandstones with considerable range in texture. Were it not for established usage the Rico and the lowest Cutler (Halgaito member) might be combined in one formation....” It is for this reason that I combine the two units into the lower Cutler beds in this report.

The underlying Honaker Trail Formation of the San Juan River area was deposited as a combination of deep- and shallow-water marine carbonates interbedded with coastal-plain siltstones and sandstones (Atchley and Loope, 1993). The lower Cutler of this area reflects deposition in these same environments. The overall progradational sequence of the lower Cutler is marked by several marine transgressions in its lower part (Rico), whereas the upper part (Halgaito) is entirely continental. Murphy (1987) proposed an eolian origin for many of the red beds of the Rico and Halgaito in the San Juan River area. Her proposed model is that the red beds are, in large part, loess that was deposited downwind from eolian strata of the upper Hermosa Group and Cedar Mesa Sandstone. Several lines of evidence were used to support an interpretation of loess rather than supratidal deposits for the red siltstone. These included (1) the grain size of the siltstone is typical for loess deposits, (2) detrital dolomite rhombs are largely unabraded, (3) laminated to massive siltstone beds are the most common lithofacies, and this lithofacies lacks bedforms related to subaqueous deposition, (4) paleosols, characterized by rhizoliths and carbonate nodules, are common throughout the red-bed sequence, and (5) chaotic or disrupted bedding, which would have been caused by precipitation of halite or gypsum in a supratidal environment, is absent in the red beds. Interbedded limestone-pebble conglomerates were deposited in streams flowing through the loess deposits. Johnson (1989) described a contemporaneous depositional system in the Pennsylvanian to Permian Maroon Formation in the Eagle Basin, on the north side of the Uncompahgre uplift, that may be similar to that of the lower Cutler in this area. The paleontological data cited by Vaughn (1973) suggests a drying trend through the Cutler of this area, but the fauna and flora of the Halgaito indicate wetter conditions than those that followed in the upper Cutler.

CORRELATIONS

Baars (1962, 1987) stated that the Elephant Canyon Formation (lower Cutler beds of this report) grades southward from Cataract Canyon into the Cedar Mesa Sandstone and Halgaito Formation. An issue not addressed, however, is the relationship of strata mapped as Rico in Cataract Canyon (Lewis and Campbell, 1965) to the Rico of the San Juan River canyon area. Baars (1962, p. 172) assigned the San Juan River Rico to the Hermosa, thus recognizing a simple gradation of the Elephant Canyon into the Halgaito.

Examination of strata in both places and at other localities on the Monument upwarp has led me to somewhat different conclusions. In comparing lithologies, thicknesses, and the relationship of the lower Cutler to the Cedar Mesa Sandstone, I believe that the Rico of the San Juan River area correlates with the lower Cutler of Dark Canyon, Cataract Canyon, and Arch Canyon, which is just west of Bluff, Utah. The Halgaito grades northward into the Cedar Mesa, or may have been locally eroded, and is equivalent to a portion of the lower Cutler beds in areas north and west of the Confluence where the Cedar Mesa grades laterally into these beds (Baars, 1987). The Halgaito is absent in Arch, Dark, and Gypsum Canyons and over a large part of the Monument upwarp in the subsurface. Gregory (1938) noted local erosion and conglomerates at the base of the Cedar Mesa Sandstone in sections he examined in the Monument upwarp area, suggesting an unconformable relationship. My stratigraphic studies support the idea of a local unconformity there, indicating that the upwarp may have been a positive feature during or shortly after deposition of the Halgaito. These relationships are shown in figure 11. On the basis of these correlations, the Halgaito is included in the lower Cutler beds as used in this report.

This idea is not without precedent. Although they were working with limited outcrops and no subsurface data, Baker and Reeside (1929, p. 1423) showed a northward gradation of the Halgaito into the Cedar Mesa Sandstone. Plates 4 and 5 show this relationship in plan view. On plate 4, the lower Cutler is thick in the San Juan River area, thins northward over the Monument upwarp, and thickens again northwest of the Colorado River. Plate 5 shows the thickest area of Cedar Mesa Sandstone in the Hite area where the lower Cutler is thin. Baars (1962, p. 169) noted that the Halgaito also grades into the Cedar Mesa west of the Monument upwarp.

In the subsurface, the lower Cutler beds (Halgaito and Rico) can be traced eastward from the Mexican Hat area as a distinct unit above the Hermosa and below the Cedar Mesa Sandstone and equivalent beds (pl. 4). Thick limestones of the Rico eventually grade into red beds, in a manner similar to that shown on figure 4. This gradation to red beds occurs at about the Utah-Colorado State line. However, an important characteristic of the red bed interval in southwestern Colorado, northwestern New Mexico, and northeastern Arizona is the presence of abundant thin limestone beds. This interval was mapped as Halgaito Formation by Huffman and Condon (1993). In southwestern Colorado, the limestone beds pinch out in the easternmost wells, but, in New Mexico, limestone beds are abundant in the wells along the San Juan

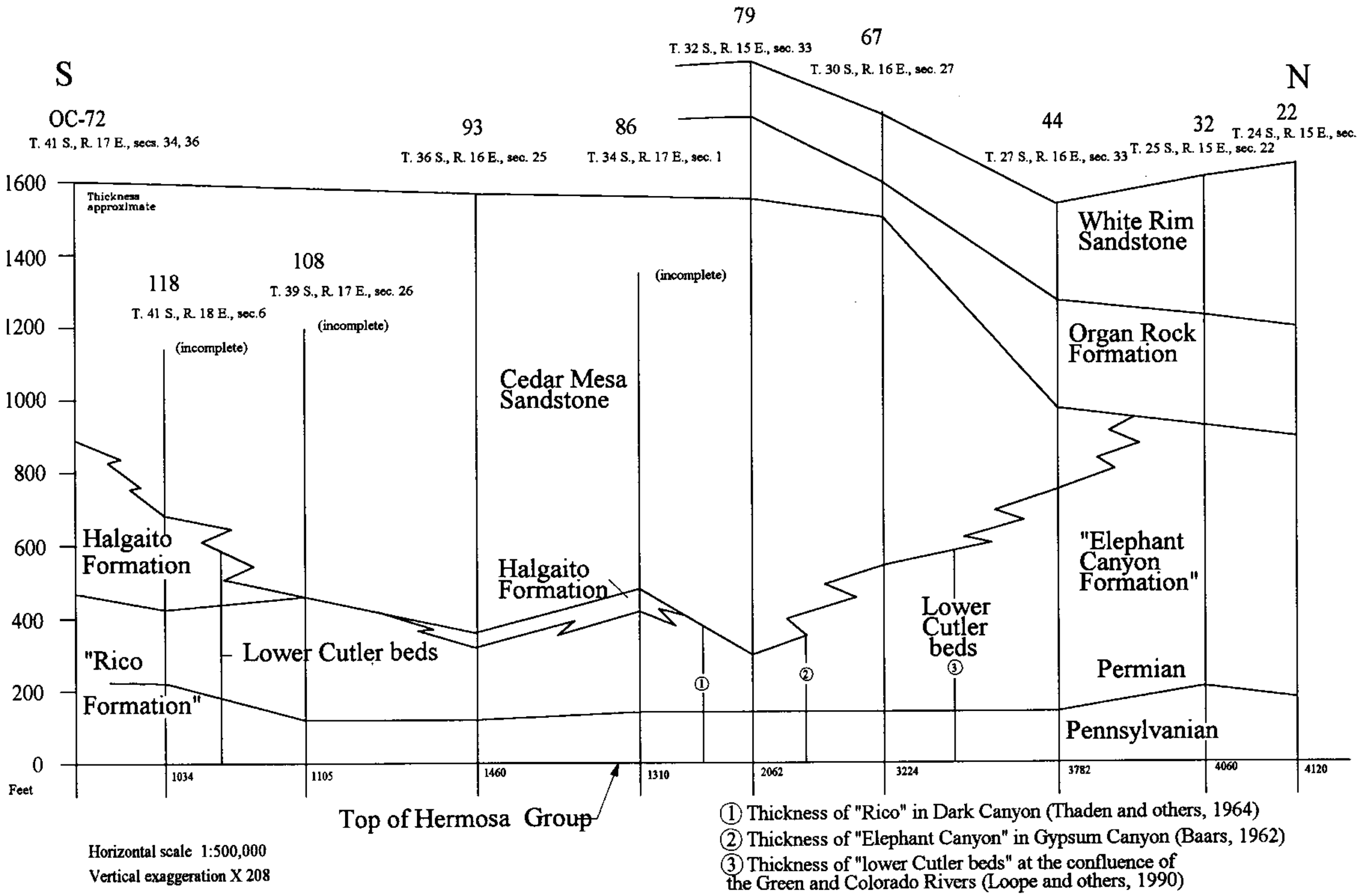

Figure 11. North-south-oriented cross section extending from the General Petroleum 45-5-G well, just east of the San Rafael Swell, to outcrops along the San Juan River, west of Mexican Hat, Utah. Location of the cross section is shown on plate 1; well numbers and outcrop number above well logs correspond to numbers on plate 1 and in Appendixes 1 and 2. Relationships show that the Halgaito Formation grades laterally into the lower part of the Cedar Mesa Sandstone north of the San Juan River. The Cedar Mesa grades into lower Cutler beds northwest of the confluence of the Green and Colorado Rivers. Lower Cutler beds include strata previously included in the Rico Formation or Elephant Canyon Formation in the north and Rico Formation or Halgaito Formation in the south. The numbers at the top of the Hermosa Group are top measured depths from the Rocky Mountain Geological

River northwest of Farmington. The southernmost well in the New Mexico data set is the only one in this area that does not contain limestone beds. Several of the holes in northeastern Arizona also contain limestone beds in the lower Cutler interval, suggesting a southeast-oriented depression in the Four Corners area in which limestones, probably of pedogenic origin, accumulated. This area also remained low during the subsequent deposition of the gypsiferous facies of the Cedar Mesa Sandstone.

Southwest and west of the Paradox Basin the lower Cutler grades into the Pakoon Limestone or Oquirrh Group, respectively (Johnson and others, 1992). These rocks were deposited in a variety of shallow- to deep-marine environments and do not show evidence of being affected by the Cutler depositional system that was tied to the Uncompahgre highlands.

AGE

Sanderson and Verville (1990) demonstrated, and Baars (1991) agreed, that the lower part of Baars' (1962) Elephant Canyon Formation is Virgilian in age. The General Petroleum 45-5-G well that was the subject of Sanderson and Verville's (1990) study is shown on figure 4 (well no. 22). Note that on figure 4 some strata assigned to the Elephant Canyon by Baars (1987) in this well are included in the Honaker Trail Formation in this report. The pick for the Honaker Trail in this and adjacent wells is based on data from the Rocky Mountain Geological Databases data set. As shown on figure 4, the lower part of the lower Cutler beds is Virgilian in age and the upper part is Wolfcampian. The Virgilian carbonates can be traced to the southeast to a point just southeast of the Colorado River, where they grade into red beds. Southeast of this pinch-out, strata of the lower Cutler and the Cutler Formation, undivided, are also Virgilian and Wolfcampian in age, but the thickness of Virgilian strata is uncertain because of a lack of marine fossil-bearing limestones. Data from Franczyk and others (1995) suggest that the base of the Cutler is probably Missourian, and possibly as old as Desmoinsian, along the Uncompahgre Plateau. The Pennsylvanian-Permian boundary is also shown on figure 11, which extends from the General Petroleum 45-5-G well southward to the San Juan River. The correlations suggest that the boundary is within strata traditionally assigned to the Rico in the San Juan River area.

Deposition of the lower Cutler beds in the Paradox Basin records the filling of the basin in the Late Pennsylvanian to Early Permian. This process proceeded from east to west and north to south, with clastic rocks derived from the Uncompahgre highlands displacing marine waters. Intermittent transgressive pulses deposited marine limestones within a mainly red-bed sequence. A marine embayment persisted in the northwest part of the basin through most or all of the Wolfcampian, and red beds of the lower Cutler grade into this marine sequence. The lobate pattern of thick and thin areas of much of the lower Cutler (pl. 4) supports an interpretation of deposition on shifting delta depocenters. Strata of the Halgaito Formation, which was only recognized in outcrop in a small area of southeastern Utah, may be more closely related to eolian processes.

CEDAR MESA SANDSTONE

The Cedar Mesa Sandstone is a thick, largely eolian sandstone that was named for a mesa adjoining the San Juan River in the Mexican Hat, Utah, area (fig. 9). The Cedar Mesa is exposed over extensive areas in the southwestern Paradox Basin along the Colorado River and on the Monument upwarp. It grades northeastward into the undivided Cutler Formation and northwestward into carbonates of the lower Cutler (Elephant Canyon of Baars, 1987). Southeast of the Monument upwarp, the Cedar Mesa undergoes a facies change to interbedded sandstone, shale and siltstone, limestone, and anhydrite or gypsum. This facies was correlated southeastward into the San Juan Basin by Huffman and Condon (1993). Southwestward, the Cedar Mesa grades into the Esplanade Sandstone, which in turn grades westward into the Pakoon Limestone and Queantoweap Sandstone (Blakey, 1979, 1990). The Cedar Mesa is thickest in the southwest part of the study area, where it is 1,330 ft thick in one well; it is 1,000 ft thick or thicker in a large area just west of the Monument upwarp (pl. 5). Due to gradation of one unit into the other, the Cedar Mesa is thickest where the lower Cutler beds are thin. The Cedar Mesa has been discussed in reports by Baker (1936, 1946), Sears (1956), Mullens (1960), Baars (1962), Witkind and Thaden (1963), Lewis and Campbell (1965), O'Sullivan (1965), Chamberlain and Baer (1973), Mack (1977), Loope (1984, 1985), Langford and Chan (1988, 1989, 1993), Stanesco and Campbell (1989), and Lockley and Madsen (1993).

The Cedar Mesa Sandstone consists of several interbedded lithofacies that vary in abundance geographically. The main lithology is light gray to yellowish gray, fine- to coarse-grained, cross-bedded and flat-bedded, quartzose sandstone. Cross-bedded cosets display small- to large-scale trough and tabular-planar cross-bedding. The size of cross-bed sets and the grain size of the sandstone decreases from northwest to southeast (Langford and Chan, 1993), and sand-sized marine fossil fragments decrease from west to east (Stanesco and Campbell, 1989). Eolian transport directions, interpreted from foreset dip orientations, are mainly to the southeast (Mack, 1977; Loope, 1984; Stanesco and Campbell, 1989). Inversely graded laminae, sand-flow toes, contorted strata, and rhizolith zones are components of the cross-bedded sandstone (Loope, 1984; Stanesco and Campbell, 1989).

Flat-bedded cosets consist of thinly bedded, horizontal to low-angle laminae and small-scale trough sets. A related facies consists of mottled and bioturbated sandstones that display poor stratification and nodules of limestone. These were interpreted as paleosols by Loope (1980) and Stanesco and Campbell (1989). Figure 8 shows the characteristic geophysical log response of the Cedar Mesa sandstone facies.

In some areas, siltstone or mudstone beds are common features of the Cedar Mesa (fig. 12). Siltstone and mudstone occur mainly around the periphery of the thickest area of Cedar Mesa (pl. 5). Some siltstone and mudstone beds are associated with fluvial strata of the undivided Cutler that interfinger with the Cedar Mesa along its northeast boundary. Other siltstone and mudstone beds are thin and lenticular and grade laterally into cross-bedded or flat-bedded eolian strata. Root casts and mud cracks are present in these beds, which were deposited in interdune areas.

Limestone beds are also associated with the Cedar Mesa in some areas. In the Gypsum Canyon area, marine limestone beds of the lower Cutler are interbedded with sandstones of the Cedar Mesa at a gradational contact (fig. 13). This type of gradational contact is common in the area northeast of Comb Wash and north of the San Juan River in the subsurface of the Paradox Basin (pl. 5). In this area, placement of the contact is somewhat arbitrary and depends on the proportions of sandstone, siltstone or shale, and limestone. Intervals consisting of mainly sandstone and a few limestones were included in the Cedar Mesa. In wells having relatively little sandstone and abundant limestone, the lithofacies were assigned to the lower Cutler.

Other limestone beds are present within the main body of the Cedar Mesa and are associated with siltstone or mudstone and flat-bedded sandstone beds. These limestones are sandy, thin, and lenticular. One limestone bed that I examined on the Monument upwarp was overlain by thick paleosols. The depositional setting of these limestone beds suggests deposition in interdune ponds.

Common features of the Cedar Mesa are laterally extensive bedding-plane surfaces that separate cross-bed cosets and flat-bedded sand-sheet strata or paleosols (figs. 9, 12). These surfaces have been related to deflation by wind to the ground-water table (Stokes, 1968; Loope, 1985) or to flooding by adjacent streams (Langford and Chan, 1988, 1993). Some surfaces can be traced for many miles along the outcrop.

The interpreted environment of deposition of the Cedar Mesa has been the subject of much discussion. Baker's (1946) initial interpretation of it as an eolian deposit was questioned by Baars (1962), who favored a marine origin. Features such as low- to moderate-angle cross-bedding, thin, horizontal sandstone beds, nature of ripple marks, numerous horizontal bedding planes, and occurrence of shale and limestone beds suggested a marginal marine to beach or "littoral" environment to Baars (1962). This interpretation was supported, in part, by Mack (1977, 1978, 1979), but Mack recognized a significant eolian component in the upper part of the Cedar Mesa. Campbell (1979) and Campbell and Steele-Mallory (1979) also recognized marine and eolian rocks in strata equivalent to the Cedar Mesa. Chamberlain and Baer (1973) reported on Thalassinid decapod burrows from uppermost beds of the Cedar Mesa that are considered indicators of a marine environment.

On the basis of wind-ripple stratification, numerous rhizolith zones, consistent transport orientations, lack of marine macrofossils, and the presence of vertebrate trackways, Loope (1981, 1984) interpreted virtually all the cross-bedded sandstone facies of the Cedar Mesa as eolian. Loope's arguments have been supported by Campbell (1986), Chan and Langford (1987), Langford and Kamola (1987), Blakey and others (1988), Langford and Chan (1988, 1989, 1993), Stanesco and Campbell (1989), and Langford and others (1990), who discussed the Cedar Mesa as an eolian deposit. Lockley and Madsen (1993) reported additional examples of vertebrate trackways in the Cedar Mesa that support a nonmarine interpretation.

These recent studies have documented eolian sedimentary features in the Cedar Mesa that make it likely that much of the formation is eolian in origin. However, on the edges of the dune field, other depositional environments exerted a greater influence. The Cedar Mesa grades northwestward into carbonate-bearing beds of the lower Cutler, and the percentage of marine fossil fragments in the Cedar Mesa increases northwestward. The source of these fossil fragments and quartz sand was most likely carbonate and siliciclastic beds that were exposed during drops in sea level or that were moved onshore during storm events. Chan and Kocurek (1988) discussed mechanisms of sediment transport in marine-influenced eolian depositional systems. Strong north-northwesterly winds (Peterson, 1988; Parrish and Peterson, 1988) moved the sediments southeastward.

The northeast side of the Cedar Mesa erg was influenced by fluvial systems draining westward and southwestward from the Uncompahgre highlands. There is a broad northwest-oriented zone of interbedded fluvial and eolian rocks that extends from about the Confluence to the Shafer dome area; isolated eolian deposits are present even farther to the northeast. Fluvial deposits and processes of fluvial-eolian interactions have been discussed by Mack (1977), Langford and Chan (1988, 1989), and Stanesco and Campbell (1989). Repeated flooding of the edge of the dune field created numerous horizontal bedding planes ("flood surfaces"), wet interdunes, and channel and flood-plain deposits.

Southeast of the Monument upwarp, the Cedar Mesa undergoes an abrupt facies change to thin eolian sandstone beds, light pink to gray shale beds, thin limestone beds, and massive gypsum or anhydrite (Sears, 1956; O'Sullivan, 1965; Stanesco and Campbell, 1989). This facies was recognized by Baars (1962), but was considered to be part of an undifferentiated lower Cutler interval. Huffman and Condon (1993) and Condon and Huffman (1994) correlated the Cedar Mesa and its equivalent gypsiferous facies southeastward into the San Juan Basin on the basis of geophysical log

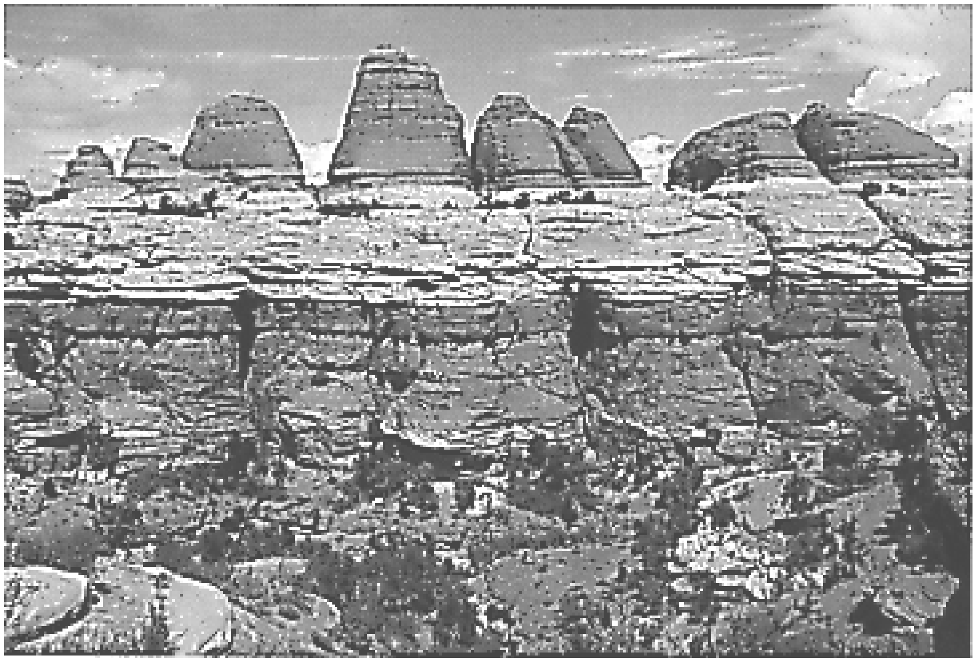

Figure 12. Interbedded sandstone, silty sandstone, and siltstone of the Cedar Mesa Sandstone just south of the confluence of the Green and Colorado Rivers. Light-colored sandstone is eolian; dark silty sandstone and siltstone were deposited in both eolian and fluvial environments. Thin limestone at base of exposure (in the trees) is the top limestone of the lower Cutler beds.

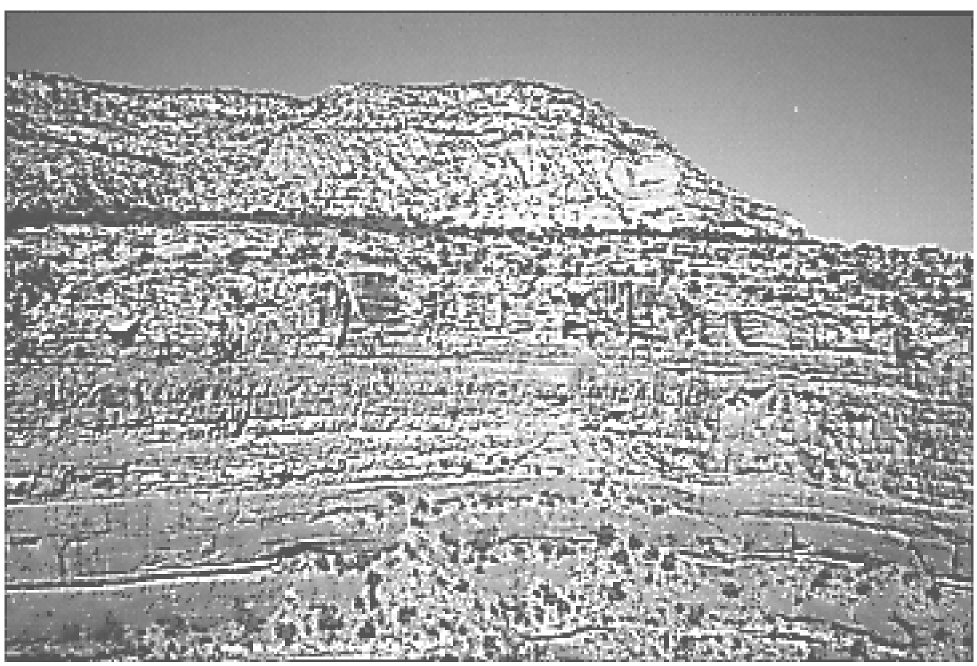

Figure 13. Cedar Mesa Sandstone (at top) and lower Cutler beds in Gypsum Canyon, just east of the Colorado River. Note transition zone at top of lower cliff where limestone beds are interbedded with light-colored Cedar Mesa beds. This is an example of the Cedar Mesa grading northward into the lower Cutler beds sequence. This relationship is shown diagrammatically on figure 11.

responses. The unit is mappable as a discrete unit over much of the northwestern San Juan Basin. Stanesco and Campbell (1989) interpreted this facies as a coastal sabkha on the basis of sulfur-, carbon-, and oxygen-isotope analyses of gypsum and limestone samples. The gypsiferous facies thins southeastward (pl. 5) as a result of gradation into the lower Cutler beds (pl. 4), in a manner similar to that shown diagrammatically on figure 11. This relationship suggests that there may have been a connection to a marine environment around the south margin of the main Cedar Mesa erg.

ORGAN ROCK FORMATION

The Organ Rock Formation is a red bed unit of the Cutler that is similar in many respects to the lower Cutler beds. It crops out around the edges of the Monument upwarp, in canyons incising Elk Ridge, and in a narrow band along the Colorado River, mainly below the Confluence. In some places in Monument Valley and near the Confluence, outliers of Organ Rock form monuments and spires. The Organ Rock is conformable with the underlying Cedar Mesa Sandstone and the overlying White Rim and De Chelly Sandstones where those units are present. Where the White Rim or De Chelly are absent, the Organ Rock is overlain unconformably by the Moenkopi or Chinle Formations. The northernmost outcrops of the unit on the east side of the Colorado River were originally referred to as the “Bogus tongue” of the Cutler by Baker (1933).

Aside from the descriptive reports of Baker (1933, 1936, 1946), Gregory (1938), Sears (1956), Mullens (1960), Witkind and Thaden (1963), Lewis and Campbell (1965), and O’Sullivan (1965), there have been few studies of the Organ Rock. Baars (1962) mapped the Organ Rock in the subsurface and discussed its regional correlations. Stanesco and Dubiel (1992); Dubiel, Huntoon, Condon, and Stanesco (1996); and Dubiel, Huntoon, Stanesco, and others (1996) reported on preliminary work concerning environments of deposition of the Organ Rock.

The Organ Rock is composed of reddish-brown to light-red, sandy siltstone; silty sandstone; mudstone; and limestone-nodule conglomerate. Alternating resistant and nonresistant beds give the formation a horizontally banded appearance (fig. 14). The geophysical log response of the Organ Rock contrasts with the underlying Cedar Mesa Sandstone (fig. 8) and the overlying White Rim Sandstone (fig. 15). In many exposures, the lower part of the Organ Rock is less sandy than the upper part and forms a broad slope at the base of overlying cliffs. Exposures of this lower part near Hite, Utah, contain sandy beds of clay-chip conglomerate. Most strata in the lower part display few sedimentary structures, although ripple marks were observed in some units. Root structures, raindrop impressions, adhesion ripples, cut-and-fill structures, low-angle cross-beds, and mud cracks are also present in some areas (J.E. Huntoon, written commun., 1995). The Organ Rock intertongues northeastward with purple arkose beds of the undivided Cutler (figs. 3*A*–3*D*). In the Paradox Basin, the Organ Rock ranges from 0 to 830 ft thick (pl. 6). Thickest areas are in southwestern Colorado and in the southeastern corner of Utah. Thinnest areas are (1) just east of Hite, and (2) on the San Rafael Swell where the Organ Rock pinches out between the White Rim Sandstone and the lower Cutler beds (fig. 3*A*). Abrupt changes in thickness along the Utah-Arizona State line may result from intertonging with either the Cedar Mesa or De Chelly Sandstones. Although difficult to document, internal unconformities may also account for thinning of the Organ Rock in some areas.

The Organ Rock was deposited in a variety of depositional environments. Stanesco and Dubiel (1992) noted mainly fluvial strata and some eolian strata in the Monument Valley area northwest of Kayenta, Ariz., and southwest of Mexican Hat, Utah. In the northern area of exposures, near the Confluence, Stanesco and Dubiel (1992) interpreted the Organ Rock as dominantly eolian. In the Hite area, a thick, salmon-colored eolian bed is present at about the middle of the Organ Rock (fig. 14). This unit displays small- to large-scale, moderate- to high-angle cross-beds. The top of this unit is highly bioturbated by plant rhizoliths similar to those described from the Cedar Mesa Sandstone by Loope (1984, 1988).

Plant and animal remains have been recovered from the Organ Rock, mainly in the Monument Valley area, and also from areas north of the San Juan River. Most fossils have been recovered from fluvial channel and associated overbank deposits. Mamay and Breed (1970) described ferns, pteridosperms, and a possible conifer from a siltstone bed in Monument Valley. The vertebrate fauna includes fish, amphibians, and reptiles, similar to the assemblage present in the Halgaito, but it lacks evidence of freshwater sharks or rhipidistian fish (Vaughn, 1973). Upward changes in fauna and flora from the Halgaito to the Organ Rock were interpreted by Vaughn (1973) to indicate increasingly arid conditions.

WHITE RIM SANDSTONE

The White Rim Sandstone is a largely eolian blanket sandstone that is present mainly west of the Colorado River (pl. 7) and is an easily identifiable unit on geophysical logs (fig. 15). It forms a highly visible white band along canyon rims; overlying strata are commonly weathered back from the rims, leaving a broad bench on top of the White Rim (fig. 16). The White Rim can be observed to thin to an erosional pinch-out in outcrops west of Moab, at Dead Horse

Figure 14. Organ Rock Formation just east of Hite, Utah. Light-colored sandstone at road level is the Cedar Mesa Sandstone. The White Rim Sandstone forms a light-colored cliff near the top of the outcrop. The Moenkopi Formation is at the top of the cliff. The lower part of the Organ Rock is finer grained than the upper part and weathers to a slope. The light sandstone in the middle of the Organ Rock is an eolian bed containing calcareous rhizoliths on its upper surface.

Point, and east of Hite, in White Canyon. It is also absent along part of the outcrop just southwest of the Confluence. It is conformably underlain by the Organ Rock Formation or the undivided Cutler Formation except in the northwestern part of the study area (fig. 3*A*), where carbonates of the lower Cutler beds underlie it (Baars, 1987). In some places, the Permian Kaibab Limestone conformably overlies or grades into the White Rim; where the Kaibab is absent, the Lower to Middle Triassic Moenkopi Formation unconformably overlies the White Rim.

Many detailed stratigraphic and sedimentologic studies have been conducted on the White Rim, beginning with Emery (1918), Gilluly and Reeside (1928), Gilluly (1929), McKnight (1940), and Baker (1946). Other studies include Baars (1962), Baars and Seager (1970), Irwin (1971, 1976), Orgill (1971), Mitchell (1985), Huntoon and Chan (1987), Steele (1987), Kamola and Chan (1988), and Chan (1989). Studies relating to the Permian-Triassic unconformity in the Paradox Basin include those by Ochs and Chan (1990) and Huntoon and others (1994).

In typical exposures, the White Rim consists of cliff-forming, grayish-white to white, fine- to coarse-grained sandstone displaying large-scale, high-angle cross-beds and flat beds. A major component of the White Rim is an eolian dune facies (Huntoon and Chan, 1987; Steele, 1987; Kamola and Chan, 1988; Chan, 1989). This facies displays high-angle cross-beds, high-index wind-ripple laminae, grainflow and grainfall strata, and inversely graded laminae, which together are indicative of an eolian environment. Transport directions were to the southeast (Steele, 1987) and south-southwest (Kamola and Chan, 1988).

Associated with the dune facies, and most fully developed at the base of the formation in the Island in the Sky district of Canyonlands, is a flat-bedded sandstone that contains algal laminations, wind-ripple strata and small-scale cross-beds, bioturbated intervals, breccia layers, adhesion ripples, and desiccation polygons (McKnight, 1940; Steele, 1987; Chan, 1989). This interval was interpreted as a sand sheet or sabkha deposit that was deposited prior to and downwind of the main dune field of the White Rim erg (Chan, 1989). Other thinner flat-bedded intervals are present within the dune facies.

In the Elaterite Basin area, west-southwest of the Confluence, and in parts of the San Rafael Swell, the upper part of the White Rim has a veneer of reworked strata. In Elaterite Basin, this unit consists of 2 to 16 ft of very fine grained to fine-grained sandstone displaying small, low-angle cross-beds, symmetrical ripple marks, fluid escape structures, rip-up clasts of the lower dune facies, chert pebbles, and large polygonal structures (Baars and Seager, 1970; Huntoon and Chan, 1987). In the San Rafael Swell, a similar sequence is 5–35 ft thick and is a mix of poorly cemented sandstone and siltstone beds interbedded with calcareous siltstone, mudstone, and carbonate beds. *Ophiomorpha* burrows were noted in this area (Orgill, 1971). Orgill (1971) documented onlapping relations of the overlying and partially equivalent

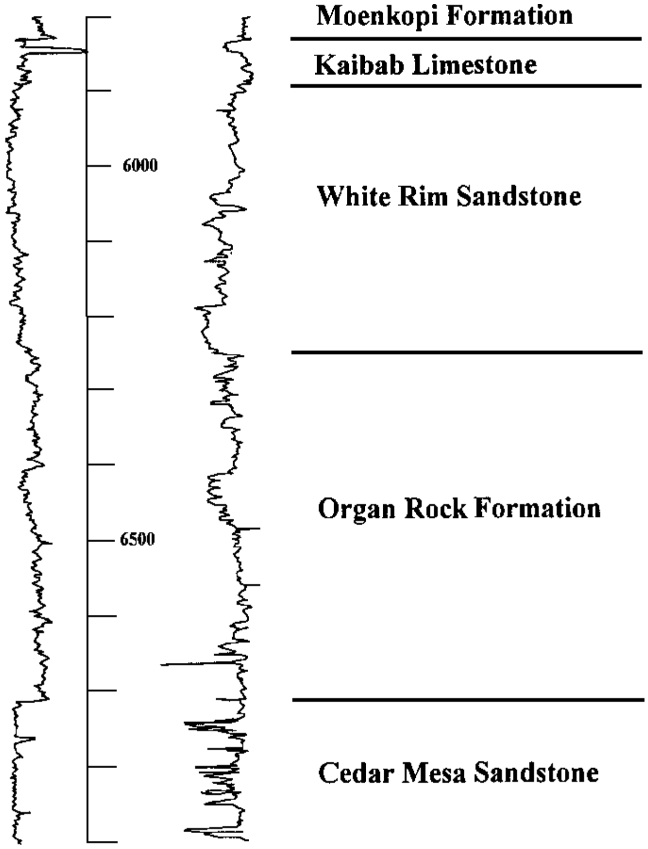

Figure 15. Well log showing the lower part of the Moenkopi Formation, Kaibab Limestone, White Rim Sandstone, Organ Rock Formation, and the top of the Cedar Mesa Sandstone in the Henry Basin on the west side of the study area. Well is number 85, plate 1 and Appendix 1. Log curves are gamma ray on the left and neutron on the right. Vertical scale is in feet.

Kaibab Limestone with the White Rim, and Huntoon and Chan (1987) described wave-cut terraces on the flanks of a dune, indicating that there is preserved dune topography at the upper surface of the White Rim. Baars and Seager (1970) interpreted all of the White Rim as a marine deposit, but subsequent studies indicate that only the upper reworked part has a marine origin. A similar reworked facies was described by Davidson (1967) in the Circle Cliffs area southwest of the Paradox Basin.

West of the Paradox Basin, the White Rim is interbedded with the Kaibab Limestone and displays abundant deformation features such as convolute bedding, microfaulting, brecciation, and sandstone dikes (Kamola and Chan, 1988). Concentrations of *Thalassinoides* and *Chondrites* burrows, indicating subaqueous (possibly marine) conditions, are present in some interbeds. Kamola and Chan interpreted the White Rim as a coastal dune field that was intermittently flooded by marine water. Steele (1987) reported glauconite throughout the White Rim, which supports this interpretation.

Although the White Rim thickens on the west side of the study area (pl. 7), it thins farther to the west and south (Mitchell, 1985). Irwin (1971, 1976) indicated that lower part of the White Rim is an eastern equivalent of the marine Toroweap Formation of northern Arizona. Rawson and Turner-Peterson (1979) described the facies relationships of the Toroweap. The upper, reworked, part of the White Rim was correlated by Irwin (1971, 1976) with the Gamma member (basal part) of the Kaibab Limestone.

The White Rim has attracted interest as an economic unit because of accumulations of hydrocarbons. The Elaterite Basin, in particular, has concentrations of tar sands that seep tar in the heat of summer (fig. 17). The dune topography preserved at the top of the White Rim is important because hydrocarbons were trapped in these high areas below the finer grained Moenkopi Formation.

DE CHELLY SANDSTONE

The De Chelly Sandstone is a massive-weathering, cross-bedded eolian sandstone that is only present in the southern part of the Paradox Basin (pl. 8). The De Chelly crops out in Monument Valley, where it forms the upper cliffs of the monuments (fig. 18), and along the western and eastern margins of the Monument upwarp. Figure 19 shows the log response of the De Chelly in the subsurface. It was named for exposures in Canyon de Chelly, which is at the southern margin of the study area, east of Chinle (pl. 8). Descriptions of the De Chelly are in Baker (1936), Gregory (1938), Sears (1956), Strobell (1956), Mullens (1960), Read and Wanek (1961), Baars (1962), Witkind and Thaden (1963), O'Sullivan (1965), Peirce (1967), Irwin (1971), and Stanesco (1991).

As typically exposed, the De Chelly consists of pinkish-brown, light-orange, tan, and gray, very fine grained to medium-grained, bimodally sorted, quartz sandstone. Many of the quartz grains are coated with red iron oxide, giving the formation its red hue. Some beds are silty, which gives the formation a banded appearance in some exposures. Vaughn (1973) noted the presence of abundant vertebrate trackways in the De Chelly; this contrasts with the White Rim Sandstone, which, despite having been extensively studied, does not have any reported trackways.

The De Chelly conformably overlies the Organ Rock Formation and has been divided into two or more parts (Read and Wanek, 1961; Peirce, 1967; Stanesco, 1991). The lower part contains small- to large-scale, high-angle cross-beds, parallel- and wavy-bedded sandstone, and minor mud-draped, ripple-laminated sandstone (Stanesco, 1991). Paleocurrents were mainly to the southeast in the lower part of the De Chelly (Read and Wanek, 1961; Stanesco, 1991). The upper part contains mainly small- to large-scale cross-beds that display dip vectors mainly to the southwest (Read and Wanek, 1961; Stanesco, 1991).

Figure 16. White Rim Sandstone, Organ Rock Formation, and top of Cedar Mesa Sandstone just southwest of the confluence of the Green and Colorado Rivers. The White Rim forms a broad bench and cliff at the top of the Organ Rock. The Cedar Mesa Sandstone undergoes a visible facies change here from interbedded light sandstone and dark siltstone beds in foreground to red beds in the distance.

The De Chelly attains a maximum thickness of 750 ft in the study area, increasing from north to south (pl. 8). Pinch-outs, caused by erosional truncation, have been noted in outcrop at the San Juan River (Baker, 1936; Mullens, 1960) and along Comb Wash (Sears, 1956; O'Sullivan, 1965). In addition to exposures on the Monument upwarp and in Canyon de Chelly, the De Chelly crops out in the Carrizo Mountains (Strobell, 1956) within the study area. The De Chelly is unconformably overlain by either the Moenkopi or Chinle Formations and grades northeastward into the undivided Cutler Formation. South of the study area, the De Chelly and equivalent rocks are overlain by the Permian San Andres Limestone, which may be time-equivalent to the Kaibab Limestone (Baars, 1979; Blakey, 1990). Blakey and Knepp (1989) and Blakey (1990) indicated that the De Chelly grades southwestward into the Coconino Sandstone and Schnebly Hill Formation in Arizona.

Stanesco (1991) studied the relationships of cross-bedded and flat-bedded facies of the De Chelly on the Defiance uplift and determined that it was deposited in eolian-dune, sand-sheet, sabkha, and mud-flat environments. From Canyon de Chelly northward, the lower part of the De Chelly is composed dominantly of large dunes of the central eolian erg; southward on the Defiance uplift, sand sheets, sabkha, and mud-flat environments dominate. The upper De Chelly is composed mainly of large dunes deposited in the central erg. A tongue of the Supai Formation, consisting of sabkha and mud-flat deposits, divides the upper and lower parts just south of the study area. Alternating facies indicate at least 12 transgressive-regressive cycles within the De Chelly (Stanesco, 1991).

Irwin (1971) and Blakey (1979) suggested that the De Chelly was related to sedimentation in the Quemado-Cuchillo or Holbrook Basins in west-central New Mexico or east-central Arizona, and the stratigraphic and facies relationships noted by Stanesco (1991) bear this out. The De Chelly erg was built up by southwest- and southeast-blowing winds and was influenced by intermittent marine transgressions from the south.

Because of their stratigraphic position above the Organ Rock Formation, the De Chelly and White Rim Sandstones have commonly been assumed to be of the same age (Baars, 1962). However, Blakey and Knepp (1989) and Blakey (1990) interpreted the De Chelly as equivalent to the Coconino Sandstone, and Irwin (1971) correlated the White Rim with the younger Toroweap and Kaibab formations. If this age disparity is correct, this suggests that there must be currently unrecognized unconformities within the Organ Rock or between the White Rim and the Organ Rock that are not present in the southern part of the area where the De Chelly crops out.

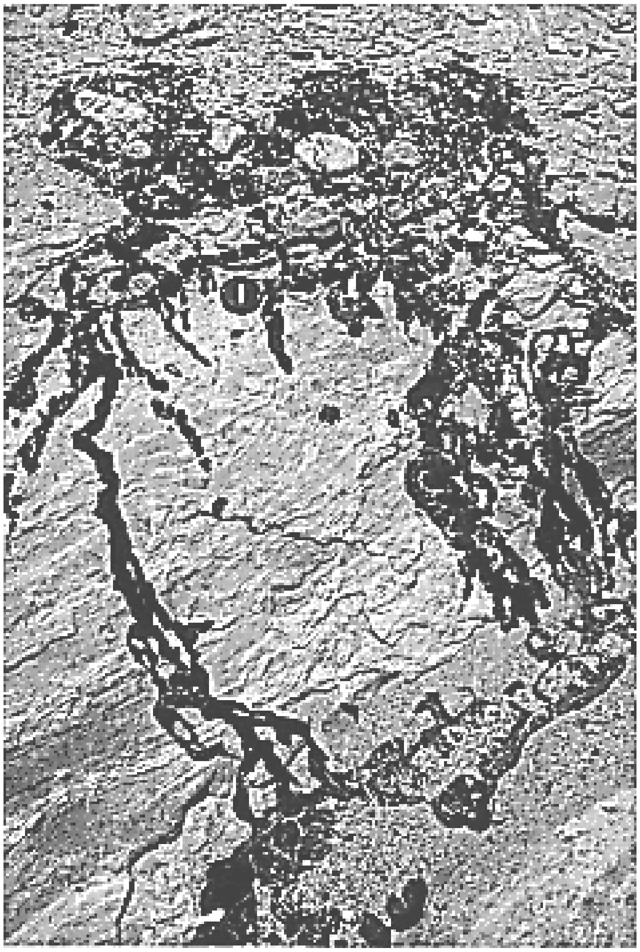

Figure 17. Tar seep from the White Rim Sandstone in Elaterite Basin, southwest of the confluence of the Green and Colorado

KAIBAB LIMESTONE

The Kaibab Limestone is only present as a thin veneer of limestone and dolomite in the western part of the Paradox Basin (pl. 9). It is irregularly distributed at the surface and in the subsurface, due to both onlapping relationships with the underlying White Rim Sandstone and to erosion at the pre-Triassic unconformity at its top. The Kaibab does not crop out anywhere within the Paradox Basin; scattered outcrops are exposed on the San Rafael Swell. As such, the unit has not received much study in the areas pertinent to this report. Studies of the unit include those by Gilluly and Reeside (1928), Gilluly (1929), Baker (1946), Davidson (1967), Irwin (1971, 1976), Orgill (1971), Kiser (1976), and Mitchell (1985). Welsh and others (1979) proposed the name “Black Box Dolomite” as a replacement for the Kaibab in part of the area discussed in this report. This name was also used by Sprinkel (1994), but not by Franczyk (1991).

In the San Rafael Swell, the Kaibab consists of gray, buff, brown, and yellowish-brown dolomite and interbedded limestone. The carbonate beds are commonly sandy, vuggy, and very fossiliferous, including coquina beds (Gilluly, 1929). Geodes lined with quartz and calcite crystals and containing dead oil residues are common features. Where present on the east side of the swell, the Kaibab forms dip slopes where the overlying Moenkopi Formation has been stripped away. Baker (1946) noted a west-to-east gradation of the Kaibab into the White Rim Sandstone, with the upper parts of the Kaibab extending farthest to the east. In the study area, the Kaibab ranges from 0 to 140 ft thick (pl. 9).

The Kaibab is also present in the Circle Cliffs uplift area (fig. 2) where it consists of thinly bedded, light-yellow dolomite. In that area, Davidson (1967) noted oolites; thin layers of green, glauconitic sandstone; and abundant moldic porosity. Geodes and stringers of bedded chert, and gray chert nodules are also present in that area. The upper part of the White Rim Sandstone there contains thin beds of fossiliferous dolomite, indicating a transgressive marine environment transitional to the Kaibab.

Irwin (1971, 1976) interpreted the Kaibab of this area as a shallow marine shelf deposit that represents the time of maximum eastward transgression of the Kaibab sea. Orgill (1971) thought that the Kaibab of the San Rafael Swell was deposited in a shallow, narrow marine embayment on a surface having marked topography. Orgill (1971) documented onlapping relationships of Kaibab carbonate beds onto knolls of White Rim Sandstone. He interpreted interbedded sandstone beds in the Kaibab as resulting from reworking of White Rim sandstones. Irwin (1971, 1976) and Kiser (1976) noted that there are petroleum shows in wells penetrating the Kaibab throughout the Colorado Plateau, making it a potentially important economic unit.

OVERLYING ROCKS

Triassic rocks unconformably overlie the Kaibab Limestone or the Cutler throughout the Paradox Basin. In most of southeastern Utah, the Moenkopi Formation is the basal Triassic unit. The lowest member of the Moenkopi, the Hoskinnini, was originally considered as the upper part of the Cutler by Baker and Reeside (1929). In most of the Colorado part of the basin, the Chinle Formation or correlative Dolores Formation overlies the Cutler. In many parts of the western Paradox Basin, the unconformity is marked by a chert-pebble conglomerate (Gilluly and Reeside, 1928; Baker, 1946; Thaden and others, 1964). This conglomerate fills channels cut into the top of the underlying Permian strata. Huntoon and others (1994) measured cross-bedding in the conglomerate and determined that flow was to the east from an area centered in the Circle Cliffs uplift area. This flow was in marked contrast to the west- and northwest-dipping paleoslope prevalent during Cutler time and during later

Figure 18. De Chelly Sandstone underlain by the Organ Rock Formation and overlain by the Moenkopi Formation at Monument Valley.

deposition of the upper part of the Moenkopi and the Chinle Formations.

PALEOGEOGRAPHY

The Cutler Group records the filling of the depositional basin that had first developed in the Middle Pennsylvanian. Deposition during the Pennsylvanian had been largely restricted to the area of the Paradox Basin, which was bounded on the northeast by the Uncompahgre uplift, on the south by the Zuni-Defiance uplift and Kaibab arch, and on the west by the Emery uplift or Piute platform (fig. 20). During the Early Permian the southern and western bounding structures had less effect, and sedimentation in the Paradox Basin had more direct interaction with shelf areas to the south and west.

The driving mechanisms for late Paleozoic deformation in the area of the Paradox Basin are not well constrained and were discussed in detail by Johnson and others (1992) and Huffman and Condon (1993). To summarize, Early Permian sedimentation in the Paradox Basin was dominated by the influence of the Uncompahgre highland, which was a westward-directed thrust block on the northeast side of the basin (fig. 20). White and Jacobson (1983) and Heyman (1983) identified many faults bounding the southwestern side of the Uncompahgre uplift, ranging from high-angle normal to high-angle reverse faults. Frahme and Vaughn (1983) estimated at least 6 mi of horizontal and 20,000 ft of vertical displacement on one of these faults.

The Uncompahgre highland itself is probably a result of northwestward-directed compression, possibly expressed as strike-slip movement, on a continental scale (Stevenson and Baars, 1986). Compression is thought to have resulted from collision of the Gondwana plate and a northern plate (fig. 20), variously called Euramerica, Laurasia, or Laurentia (Ross and Ross, 1986; Johnson and others, 1992; Huffman and Condon, 1993). Johnson and others (1992) also suggested that the geometry of the Uncompahgre uplift may have been influenced by a left-lateral transform fault that may have bounded the western continental margin.

Within this structural framework, clastics were shed from the Uncompahgre highland westward into the Paradox Basin since the Middle Pennsylvanian (Wengerd and Matheny, 1958; Franczyk and others, 1995). Sedimentation seems to have been continuous in that area throughout deposition of the Hermosa and Cutler, making the pick between units indefinite in places. Due to abundant arkosic clastics in the Hermosa Group, the composition of clastic rocks cannot be used as a criteria for separating the units. Franczyk (1992) and Franczyk and others (1995) noted that the boundary between the Hermosa and Cutler is gradational in the Durango, Colo., area. They placed the contact at the top of the highest carbonate bed of probable marine origin, which is also at the color change from gray and green beds to red beds. The youngest Hermosa strata in that area are Desmoinsian in age, suggesting that the age of the Cutler is

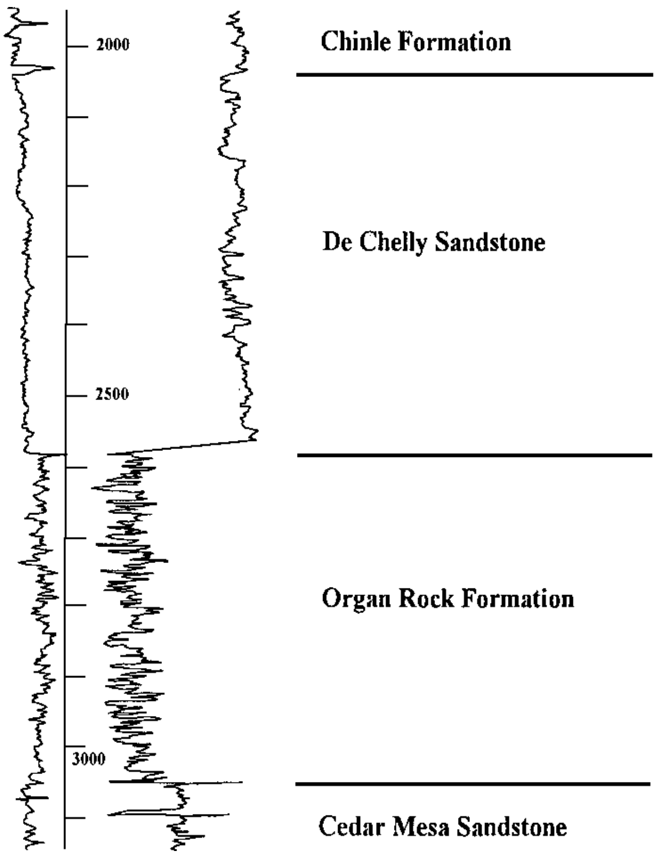

Figure 19. Well log showing the lower part of the Chinle Formation, De Chelly Sandstone, Organ Rock Formation, and the top of the Cedar Mesa Sandstone on the northwest flank of the Defiance uplift, northeastern Arizona. Well is number 134, plate 1 and Appendix 1. Log curves are gamma ray on the left and interval transit time on the right. Vertical scale is in feet.

no younger than Missourian, and possibly Desmoinsian, there.

In much of the central Paradox Basin, the contact between the Hermosa and Cutler is also made at the highest marine carbonate bed (fig. 4). However, along the western side of the basin, marine carbonates formerly included in the Rico Formation or Elephant Canyon Formation interfinger with red beds and are included in the lower part of the Cutler. These strata range in age from Virgilian to Wolfcampian (Baars, 1962, 1991; Sanderson and Verville, 1990). Initiation of Cutler deposition thus possibly began as early as Middle Pennsylvanian (Desmoinsian) in alluvial fans and debris flows along the margin of the Uncompahgre highlands. These alluvial sediments graded westward into marine strata of Virgilian and Wolfcampian age in northern Arizona and central Utah in marginal marine to deltaic environments.

Figure 21 shows the paleogeography of the Paradox Basin in Early Permian (Wolfcampian) time. At this time, the basin was situated just north of the Equator and was rotated as much as 45° clockwise from its present position. Prevailing winds blew from northeast to southwest (present-day coordinates), but there was a significant southeastward component (Parrish and Peterson, 1988; Peterson, 1988), possibly caused by an eddy effect around the north end of the Uncompahgre highlands. Streams still drained the Uncompahgre, flowing to the west-northwest and southwest, while Wolfcampian carbonates and clastics were being deposited off the northwestern end of the Paradox Basin. A large coastal dune field (Cedar Mesa Sandstone) was deposited just downwind of the carbonates; significant amounts of marine fossil clasts in the Cedar Mesa indicate that the source of much of the sand must have been exposed carbonate and clastic beds during lowstands of the sea. Some of the clastics were undoubtedly derived from streams flowing from the Uncompahgre highland into the sea, but another source may have been marine sand moved southward from the Wyoming shelf (Baars, 1962; Johnson and others, 1992). Fluvial-eolian interactions occurred along the northeastern edge of the Cedar Mesa erg, and distal streams partially fed a large sabkha in the Four Corners area. Strong unidirectional winds moved sand from northwest to southeast; the area around Mexican Hat, Utah, may have been the site of loess deposition downwind from the main erg. The morphology of dunes in the Cedar Mesa indicates transverse to barchan dune forms. The main mass of the Cedar Mesa Sandstone was deposited just to the west of the Monument upwarp; the abrupt facies change to thin clastic, gypsum, and limestone beds deposited in a sabkha occurs on the east flank of the upwarp. This relationship suggests that the Monument upwarp was a slight topographic high during deposition of the Cedar Mesa and that the Four Corners area was a topographic low. A low in this area had persisted since deposition of the lower Cutler beds (Halgaito Formation), shown by numerous limestone beds within the red bed sequence.

Figure 22 shows a paleogeographic reconstruction in Leonardian to Guadalupian time for the Paradox Basin. The Uncompahgre highlands were still high enough to shed alluvial arkosic sediment to the west, southwest, and south. In the northwestern part of the study area, first the Toroweap and later the Kaibab seas interfingered eastward with the coastal White Rim Sandstone erg. Wind transport directions in the White Rim are similar to those of the Cedar Mesa, mainly to the southeast. In the southern part of the area, the slightly older De Chelly erg also developed. Stratigraphic relationships indicate that a marine environment existed south of the De Chelly erg, in eastern Arizona and west-central New Mexico. Although the lower De Chelly also displays wind transport to the southeast, the upper part of the unit was deposited by winds blowing more to the southwest.

In an area on the west flank of the Monument upwarp in the west-central part of the Paradox Basin, the White Rim and De Chelly are absent and the Organ Rock

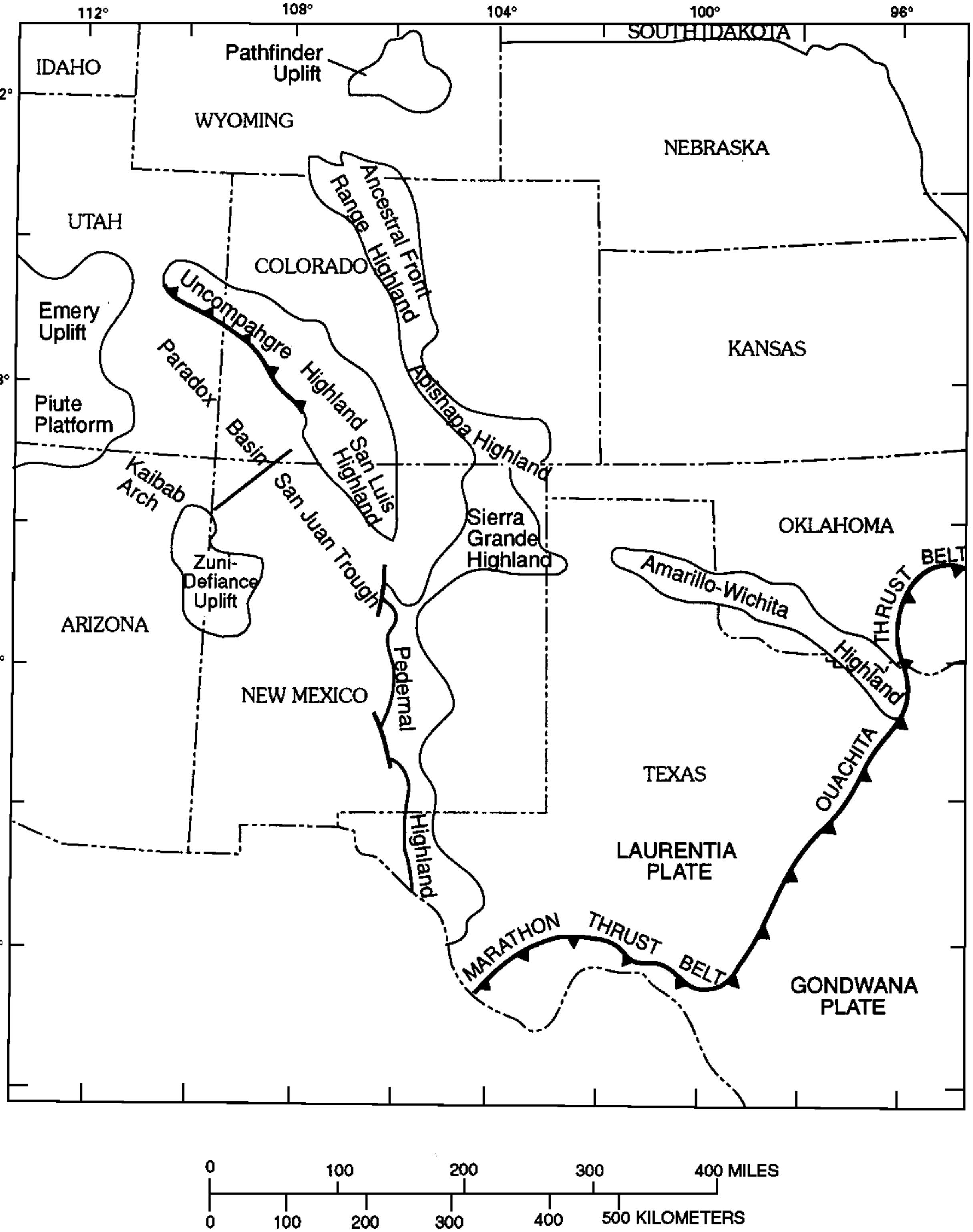

Figure 20. Late Paleozoic structural elements in the southwestern United States. Modified from Huffman and Condon (1993).

is relatively thin (pl. 6, 7, 8). This suggests that the upwarp may have still been an active structure during deposition of the Organ Rock and possibly during deposition of the White Rim and De Chelly. Two factors have combined to conceal stratigraphic relations between the White Rim and De Chelly in this area: (1) post-depositional erosion has removed both units over the crest of the Monument upwarp, and (2) there has been little or no

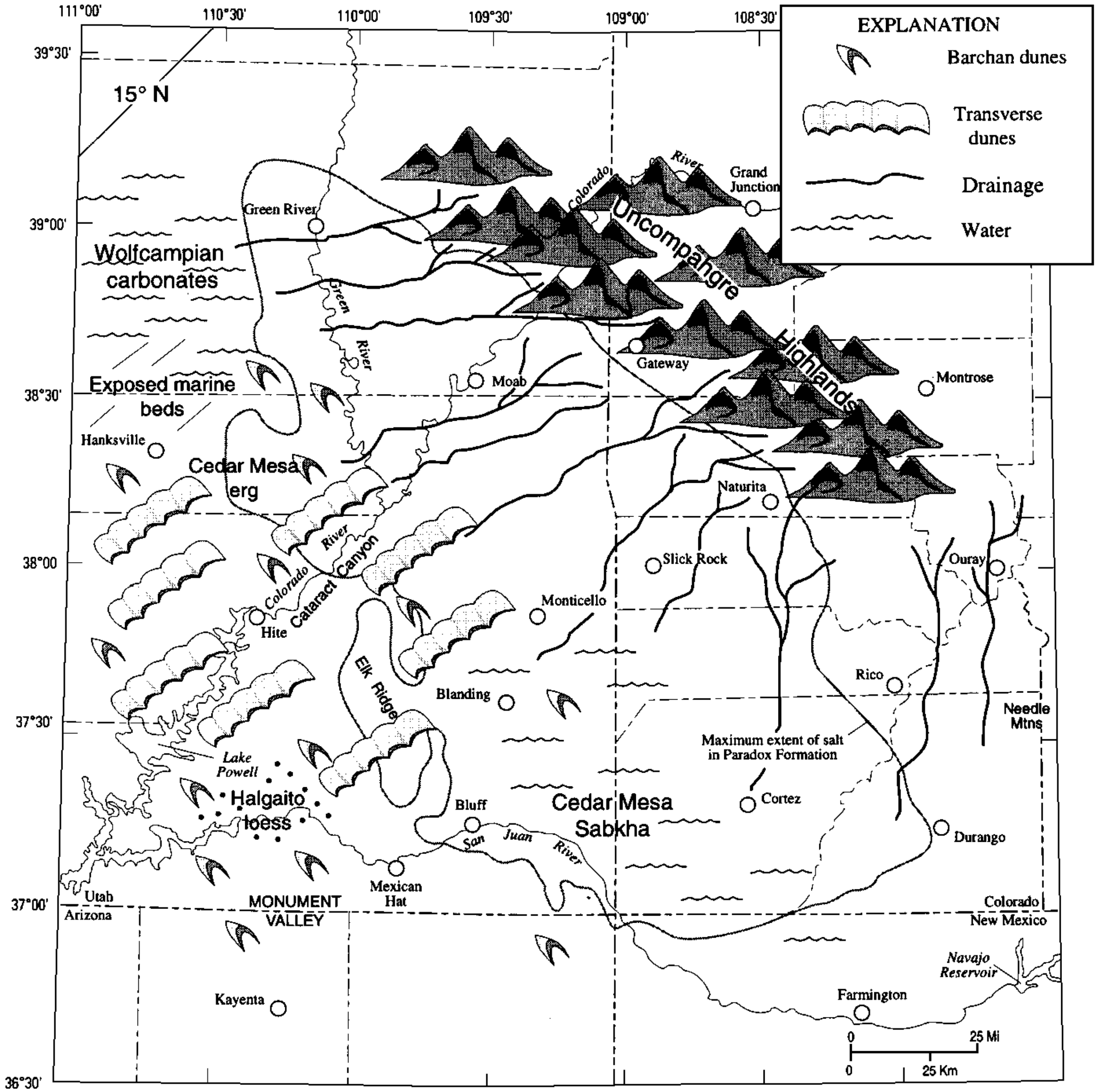

Figure 21. Paleogeography of the Paradox Basin area in Early Permian (Wolfcampian) time. Sources include Mack (1977), Campbell

drilling between Hite and the San Juan River. Irwin (1971, p. 1989) interpreted strata in the Skelly Oil Co. Nokai Dome 1 well as representing the De Chelly overlain by White Rim and thus believed that the two units are not correlatives. No other well data has become available in the time since that interpretation. Until more wells are drilled between Hite and the San Juan River, the question can not be resolved conclusively.

At the close of the Permian, the Uncompahgre uplift had been worn down to the point that it was no longer a sediment source. The site of the Paradox Basin underwent erosion or nondepostion during the remainder of the Guadalupian and Ochoan and into the Early Triassic. A short-lived orogeny just to the west of the Paradox Basin caused a temporary change in paleoslope to the east and deposition of fluvial conglomerate in channels cut into the upper surface of Cutler strata in places. Later in the Trias-

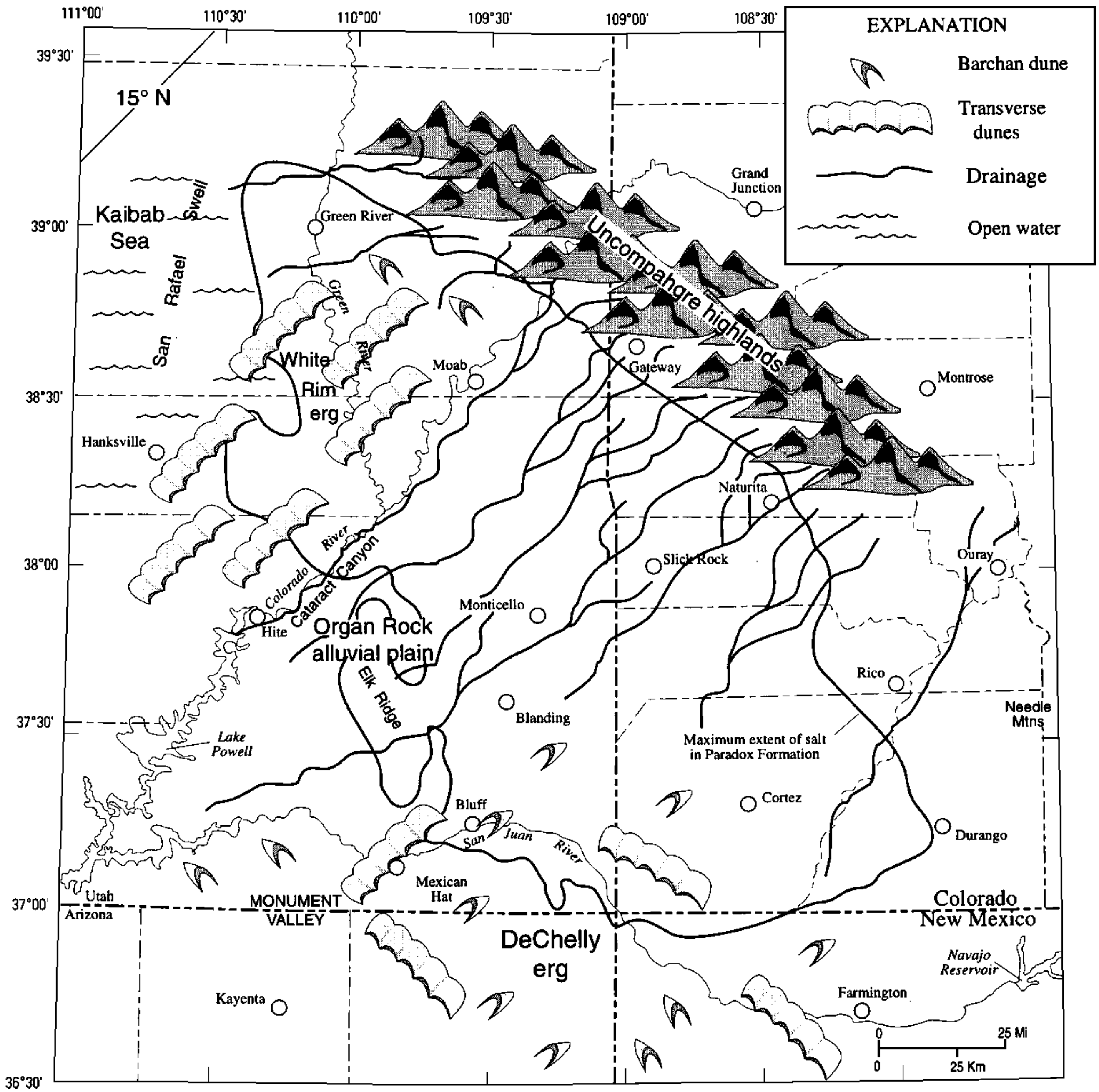

Figure 22. Paleogeography of the Paradox Basin area in Early to Late Permian (Leonardian to Guadalupian) time. Sources include Steele (1987), Chan (1989), and Stanesco (1991). Paleolatitude (15° N.) from Scotese and McKerrow (1990).

sic, the Uncompahgre again became established as a sediment source for part of the Moenkopi, Dolores, and Chinle Formations and a westward paleoslope was again established.

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APPENDIXES

Appendix 1. Drill holes used as control points for maps and cross sections.

[Table is sorted by township, range, and section within States. The last two digits in the location column denote the position of the well within the section; each section is divided into 16 parts., number 01 is in the NE¼NE¼ and number 16 is in the SE¼SE¼. The divisions are numbered horizontally]

No.	Company	Well name	Location	County
		UTAH		
1	Diamond Shamrock Oil & Gas Corp	Witter Federal, No. 1	T. 18 S., R. 15 E., sec. 19 02	Emery.
2	Reynolds Mining Corporation	Cedar Mountain Unit, No. 1	T. 19 S., R. 12 E., sec. 29 11	Emery.
3	Humble Oil & Refining Co	Woodside Unit, No. 1	T. 19 S., R. 13 E., sec. 12 16	Emery.
4	American Metal Climax Inc	Black Dragon Government, No. 1	T. 21 S., R. 13 E., sec. 32 09	Emery.
5	Megadon Enterprises Inc	Saleratus Federal State, No. 2-36	T. 21 S., R. 14 E., sec. 36 04	Emery.
6	Superior Oil Company	Grand Fault Unit, No. 14-24	T. 21 S., R. 15 E., sec. 24 13	Emery.
7	Mobil Oil Corporation	Elba Flats Unit, No. 1-30	T. 21 S., R. 22 E., sec. 30 07	Grand.
8	Reynolds Mining Corporation	Sinbad Unit, No. 1	T. 22 S., R. 12 E., sec. 26 02	Emery.
9	Amax Petroleum Corporation	Green River Desert Unit, No. 9-7	T. 22 S., R. 15 E., sec. 09 07	Emery.
10	Continental Oil Company	Crescent Unit, No. 1	T. 22 S., R. 20 E., sec. 17 12	Grand.
11	Amerada Petroleum Corporation	Sinbad Strat, No. 1-354	T. 23 S., R. 10 E., sec. 28 07	Emery.
12	Kerr McGee Oil Industries	TP Utah 27, No. 1	T. 23 S., R. 13 E., sec. 07 08	Emery.
13	Forest Oil Corporation	Forest Government, No. 1	T. 23 S., R. 14 E., sec. 11 01	Emery.
14	Lion Oil Co (Monsanto Chem Co.)	Hatt Federal, No. 1	T. 23 S., R. 14 E., sec. 19 16	Emery.
15	Shell Oil Company	Chaffin Unit, No. 1	T. 23 S., R. 15 E., sec. 21 03	Emery.
16	Mobil Oil Corporation	Jakey's Ridge, No. 12-3	T. 23 S., R. 16 E., sec. 03 05	Emery.
17	Pan American Petroleum Corporation	Salt Wash, No. 1	T. 23 S., R. 17 E., sec. 15 12	Grand.
18	Texaco Inc	Government McKinnon, No. 1	T. 23 S., R. 19 E., sec. 15 13	Grand.
19	Blackwood Nichols Co Ltd	San Rafael, No. 1-28	T. 24 S., R. 10 E., sec. 28 11	Emery.
20	Superior Oil Company	Iron Wash Unit, No. 23-2	T. 24 S., R. 13 E., sec. 02 11	Emery.
21	Union Texas Petroleum	Federal Armstrong, No. 1	T. 24 S., R. 14 E., sec. 10 01	Emery.
22	General Petroleum Corporation	No. 45-5-G	T. 24 S., R. 15 E., sec. 05 11	Emery.
23	Shell Oil Company	Gruvers Mesa Federal, No. 1	T. 24 S., R. 16 E., sec. 19 07	Emery.
24	Megadon Energy Corporation	Ten Mile, No. 1-26	T. 24 S., R. 17 E., sec. 26 13	Grand.
25	Phillips Petroleum Company	Onion Creek Unit, No. 2	T. 24 S., R. 23 E., sec. 13 07	Grand.
26	Conoco Inc	Conoco Federal, No. 31-1	T. 24 S., R. 23 E., sec. 31 10	Grand.
27	Exxon Corporation	Onion Creek Federal, No. 1	T. 24 S., R. 25 E., sec. 18 05	Grand.
28	Pan American Petroleum Corporation	USA Brown, No. 1	T. 25 S., R. 12 E., sec. 24 04	Emery.
29	Union Oil Company of California	Temple Wash Gov't 988, No. A-1	T. 25 S., R. 13 E., sec. 11 04	Emery.
30	Texaco Inc	Temple Springs Unit, No. 1	T. 25 S., R. 13 E., sec. 14 04	Emery.
31	Texaco Inc	Temple Springs Unit, No. 2	T. 25 S., R. 14 E., sec. 22 14	Emery.
32	Continental Oil Company	Moonshine Wash Unit, No. 2	T. 25 S., R. 15 E., sec. 22 07	Emery.
33	Superior Oil Company	Bow Knot Unit, No. 43-20	T. 25 S., R. 17½ E., sec. 20 09	Grand.
34	Pan American Petroleum Corporation	Nequoia Arch Unit, No. 9	T. 26 S., R. 13 E., sec. 25 12	Emery.
35	Carter Oil Company	Nequoia Arch Unit, No. 3	T. 26 S., R. 14 E., sec. 26 16	Emery.
36	Davis Oil Company	Pool Unit, No. 1	T. 26 S., R. 17 E., sec. 17 13	Emery.
37	Pure Oil Company	USA Mineral Point, No. 1	T. 26 S., R. 18 E., sec. 07 09	Grand.
38	Southern Natural Gas Company	Long Canyon Unit, No. 1	T. 26 S., R. 20 E., sec. 09 06	Grand.
39	Texas Gulf Producing Company	Federal, No. 1-X	T. 26 S., R. 20 E., sec. 36 09	Grand.
40	Union Oil Company of California	Burkholder Unit, No. 1-G-1	T. 26 S., R. 22 E., sec. 01 07	Grand.
41	Carter Oil Company	Blackburn Draw Unit, No. 1	T. 27 S., R. 12 E., sec. 09 01	Wayne.
42	Superior Oil Company	Hanksville Unit, No. 31-30	T. 27 S., R. 13 E., sec. 30 02	Wayne.
43	Texaco Inc	Nequoia Arch Unit, No. 6	T. 27 S., R. 15 E., sec. 32 08	Wayne.
44	Superior Oil Company	Horseshoe Can. Unit, No. 32-33	T. 27 S., R. 16 E., sec. 33 07	Wayne.

Appendix 1. Drill holes used as control points for maps and cross sections—*Continued.*

No.	Company	Well name	Location	County
		UTAH—*Continued*		
45	Southern Natural Gas Company	USA, No. 2	T. 27 S., R. 20 E., sec. 06 11	San Juan.
46	Underwood Rip C	Featherstone, No. 9-1	T. 27 S., R. 20 E., sec. 09 01	San Juan.
47	Megadon Energy Corporation	Lion Mesa, No. 34-2	T. 27 S., R. 21 E., sec. 34 11	San Juan.
48	Larue E B Jr	Government, No. 1	T. 27 S., R. 22 E., sec. 15 08	San Juan.
49	Exxon Corporation	Gold Basin Unit, No. 1	T. 27 S., R. 24 E., sec. 15 04	San Juan.
50	Murphy Corporation	Nequoia Arch Unit, No. 4	T. 28 S., R. 14 E., sec. 14 13	Wayne.
51	Pan American Petroleum Corporation	Murphy Range Unit, No. 1	T. 28 S., R. 18 E., sec. 12 03	San Juan.
52	Gulf Oil Corporation	Aztec Lockhart Federal, No. 1	T. 28 S., R. 20 E., sec. 22 12	San Juan.
53	Pan American Petroleum Corporation	USA Lockhart, No. 1	T. 28 S., R. 20 E., sec. 23 16	San Juan.
54	Richfield Oil Corporation	Hatch Mesa, No. 1	T. 28 S., R. 21 E., sec. 22 11	San Juan.
55	Gulf Oil Corporation	Red Rock Unit, No. 1	T. 28 S., R. 22 E., sec. 09 02	San Juan.
56	Gulf Oil Corporation	Hudson Wash Federal, No. 1	T. 28 S., R. 22 E., sec. 34 01	San Juan.
57	Amerada Petroleum Corporation	Blue Mesa Unit, No. 1	T. 29 S., R. 10 E., sec. 08 13	Wayne.
58	Tennessee Gas Transmission Co	USA Sorrel Butte, No. 1-A	T. 29 S., R. 12 E., sec. 33 07	Wayne.
59	Phillips Petroleum Company	Dirty Devil Federal, No. 17-58-A	T. 29 S., R. 13 E., sec. 01 01	Wayne.
60	Continental Oil Company	Hoover Federal, No. 1	T. 29 S., R. 15 E., sec. 20 08	Wayne.
61	Humble Oil & Refining Company	Rustler Dome, No. 1	T. 29 S., R. 20 E., sec. 04 12	San Juan.
62	Husky Oil Company	Federal, No. 15-25	T. 29 S., R. 23 E., sec. 25 15	San Juan.
63	Superior Oil Company	Horse Thief Canyon Unit, No. 1-5	T. 29 S., R. 26 E., sec. 05 16	San Juan.
64	Reynolds Mining Corporation	Gibson Dome Unit, No. 1	T. 29½ S., R. 20 E., sec. 35 08	San Juan.
65	Southland Royalty Company	Burr Desert, No. 1	T. 30 S., R. 12 E., sec. 24 08	Wayne.
66	Paradox Production; Putnam & Smoot	Federal, No. 1	T. 30 S., R. 13 E., sec. 34 02	Wayne.
67	Phillips Petroleum Company	French Seep, No. 1	T. 30 S., R. 16 E., sec. 27 06	Wayne.
68	Trident Oil Company	Beef Basin Unit, No. 4	T. 30 S., R. 19 E., sec. 26 12	San Juan.
69	Pure Oil Company	Lost Canyon, No. 1	T. 30 S., R. 20 E., sec. 19 15	San Juan.
70	Trident Oil Company	Beef Basin Unit, No. 5	T. 30 S., R. 20 E., sec. 32 03	San Juan.
71	Apache Drilling Company	Apache Lion Lisbon, No. 1	T. 30 S., R. 23 E., sec. 13 09	San Juan.
72	Pure Oil Company	Northwest Lisbon, No. 1	T. 30 S., R. 24 E., sec. 10 03	San Juan.
73	Kern County Land Co; Skelly Oil	Crescent Creek, No. 1-X	T. 31 S., R. 11 E., sec. 27 16	Garfield.
74	Superior Oil Company	Utah Southern Gov't, No. 22-19	T. 31 S., R. 15 E., sec. 19 06	Garfield.
75	Chorney Oil Company et al.	Hart Point Federal, No. 1-22	T. 31 S., R. 22 E., sec. 22 12	San Juan.
76	Skelly Oil Company	Church Rock Unit, No. 1	T. 31 S., R. 23 E., sec. 26 06	San Juan.
77	Skelly Oil Company	Summit Point, No. 1	T. 31 S., R. 25 E., sec. 21 13	San Juan.
78	Lone Star Producing Company	Federal Utah A, No. 1	T. 31 S., R. 26 E., sec. 18 02	San Juan.
79	Texas Pacific Coal and Oil Company	USA, No. 1	T. 32 S., R. 15 E., sec. 33 02	Garfield.
80	Texas Company	Cataract Canyon Unit, No. 1	T. 32 S., R. 19 E., sec. 28 10	San Juan.
81	Southland Royalty Company	Hog Canyon, No. 1	T. 33 S., R. 13 E., sec. 08 04	Garfield.
82	Natomas North America Inc	Redd Ranch, No. 1-34A	T. 33 S., R. 20 E., sec. 34 16	San Juan.
83	Byrd Frost Inc	Randall, No. 1	T. 33 S., R. 24 E., sec. 23 06	San Juan.
84	Carter Oil Company	Leverton State, No. 1	T. 33 S., R. 26 E., sec. 32 13	San Juan.
85	Superior Oil Company	Swap Mesa Unit, No. 14-2	T. 34 S., R. 09 E., sec. 02 13	Garfield.
86	Sinclair Oil & Gas Company	Dark Canyon Unit, No. 2	T. 34 S., R. 17 E., sec. 01 12	San Juan.
87	White Canyon Mining Company	Frost, No. 1	T. 34 S., R. 24 E., sec. 23 05	San Juan.
88	Skelly Oil Company	Utah Federal C, No. 1	T. 35 S., R. 15 E., sec. 04 13	San Juan.
89	Lemm & Maiatico	Dry Mesa Government, No. 1	T. 35 S., R. 18 E., sec. 02 13	San Juan.
90	Standard Oil Company of California	Johnson Creek, No. 2	T. 35 S., R. 22 E., sec. 32 01	San Juan.

Appendix 1. Drill holes used as control points for maps and cross sections—*Continued.*

No.	Company	Well name	Location	County
		UTAH—*Continued*		
91	Pan American Petroleum Corporation	Montezuma Canyon Unit, No. 1	T. 35 S., R. 24 E., sec. 33 10	San Juan.
92	Gulf Oil Corporation	Coalbed Canyon Unit, No. 2	T. 35 S., R. 26 E., sec. 20 08	San Juan.
93	Sinclair Oil & Gas Company	McLane Federal, No. 1	T. 36 S., R. 16 E., sec. 25 01	San Juan.
94	Pan American Petroleum Corporation	Bears Ears, No. 1	T. 36 S., R. 19 E., sec. 17 16	San Juan.
95	Southland Royalty Company	Red Canyon, No. 1	T. 37 S., R. 14 E., sec. 03 11	San Juan.
96	Kern County Land Company	Moqui Federal, No. 1-X	T. 37 S., R. 15 E., sec. 33 03	San Juan.
97	Kubat Edward J	Government, No. 1	T. 37 S., R. 19 E., sec. 23 13	San Juan.
98	Cities Service Oil & Gas Corporation	State A, No. 1	T. 37 S., R. 23 E., sec. 32 03	San Juan.
99	Pan American Petroleum Corporation	Deadman Canyon Unit, No. 1	T. 37 S., R. 24 E., sec. 20 02	San Juan.
100	Champlin Petroleum Company	Chaparral Unit, No. 1	T. 37 S., R. 25 E., sec. 22 14	San Juan.
101	Carter Oil Company	Ryan J, No. 1	T. 38 S., R. 18 E., sec. 14 04	San Juan.
102	Great Western Drilling Company	Fish Creek, No. 1	T. 38 S., R. 20 E., sec. 22 04	San Juan.
103	Larue E B Jr	Butler Wash, No. 1	T. 38 S., R. 21 E., sec. 03 01	San Juan.
104	Fair Ralph E	Butler Wash, No. 1-A	T. 38 S., R. 21 E., sec. 16 12	San Juan.
105	Houston Oil & Minerals Corporation	Federal, No. 11-6	T. 39 S., R. 14 E., sec. 06 04	San Juan.
106	Forest Oil Corporation	Government, No. 1-31	T. 39 S., R. 15 E., sec. 31 06	San Juan.
107	Sinclair Oil & Gas Company	Grand Gulch Federal, No. 1	T. 39 S., R. 16 E., sec. 15 15	San Juan.
108	Carter Oil Company	Government Hancock, No. 1	T. 39 S., R. 17 E., sec. 26 08	San Juan.
109	Carter Oil Company	Cedar Mesa Unit, No. 1	T. 39 S., R. 18 E., sec. 15 03	San Juan.
110	Atlantic Refining Company	Comb Wash Unit, No. 1	T. 39 S., R. 20 E., sec. 14 10	San Juan.
111	Carter Oil Company	Bluff Bench Unit, No. 1	T. 39 S., R. 22 E., sec. 29 12	San Juan.
112	Shell Oil Company	Bluff Unit, No. 1	T. 39 S., R. 23 E., sec. 32 02	San Juan.
113	Reynolds Mining Corporation	Hatch Unit, No. 1	T. 39 S., R. 24 E., sec. 04 01	San Juan.
114	Skelly Oil Company	Nokai Unit, No. 1-A	T. 40 S., R. 12 E., sec. 27 04	San Juan.
115	Norris Oil Company	Navajo, No. 1-34	T. 40 S., R. 23 E., sec. 34 13	San Juan.
116	Texaco Inc	Navajo Tribe D, No. 30	T. 40 S., R. 24 E., sec. 20 03	San Juan.
117	Shell Oil Company	Hovenweep, No. 2	T. 40 S., R. 26 E., sec. 09 15	San Juan.
118	Texaco Inc	Johns Canyon Unit, No. 1	T. 41 S., R. 18 E., sec. 06 13	San Juan.
119	Texaco Inc	Navajo V, No. 1	T. 41 S., R. 20 E., sec. 36 04	San Juan.
120	Texas Company	Navajo Tribe R, No. 6	T. 41 S., R. 24 E., sec. 01 12	San Juan.
121	Skelly Oil Company	Mexican Hat, No. 1	T. 42 S., R. 19 E., sec. 10 15	San Juan.
122	Gulf Oil Corporation	White Mesa, No. 1	T. 42 S., R. 23 E., sec. 27 01	San Juan.
123	Davis Oil Company	Superior Navajo, No. 1	T. 42 S., R. 24 E., sec. 15 04	San Juan.
124	Pan American Petroleum Corporation	Navajo 161, No. 1	T. 43 S., R. 20 E., sec. 06 14	San Juan.
125	Cities Service Oil & Gas Corporation	Navajo B, No. 1	T. 43 S., R. 20 E., sec. 36 06	San Juan.
126	Western Natural Gas Company	English, No. 1	T. 43 S., R. 22 E., sec. 22 03	San Juan.
127	Sunray DX Oil Company	Utah Navajo B, No. 1	T. 43 S., R. 23 E., sec. 04 06	San Juan.
		ARIZONA		
128	Humble Oil & Refining Company	Navajo 138, No. 2	T. 35 N., R. 30 E., sec. 06 16	Apache.
129	Kerr McGee Corporation	Navajo H, No. 1	T. 35 N., R. 30 E., sec. 14 01	Apache.
130	Riddle and Gottlieb	Navajo 8841, No. 1	T. 36 N., R. 27 E., sec. 30 05	Apache.
131	Vaughey Vaughey & Blackburn	Navajo 8805, No. 6-1	T. 36 N., R. 28 E., sec. 06 04	Apache.
132	Union Oil Company of California	Navajo 3741 Lukachukai, 1-P-4	T. 36 N., R. 29 E., sec. 04 16	Apache.
133	Buttes Gas and Oil Company	Navajo, No. 1-24	T. 37 N., R. 28 E., sec. 24 09	Apache.
134	Pan American Petroleum Corporation	Navajo Tribal T, No. 1	T. 38 N., R. 27 E., sec. 20 16	Apache.
135	Skelly Oil Company	Navajo Q, No. 1	T. 38 N., R. 30 E., sec. 18 04	Apache.

Appendix 1. Drill holes used as control points for maps and cross sections—*Continued.*

No.	Company	Well name	Location	County
		ARIZONA—*Continued*		
136	Cactus Drilling Corporation	Navajo Rock Point, No. 1	T. 39 N., R. 26 E., sec. 19 12	Apache.
137	Occidental Petroleum Corporation	Monument Navajo, No. 1	T. 41 N., R. 22 E., sec. 12 12	Apache.
138	Gulf Oil Corporation	Garnet Ridge Navajo, No. 1	T. 41 N., R. 24 E., sec. 16 01	Apache.
139	Texaco Inc	Navajo AG, No. 2	T. 41 N., R. 25 E., sec. 21 02	Apache.
140	Tenneco Oil Company	Navajo 4332, No. 1	T. 41 N., R. 26 E., sec. 33 13	Apache.
140	Shell Oil Company	Navajo, No. 2	T. 41 N., R. 28 E., sec. 03 06	Apache.
		COLORADO		
142	Pure Oil Company	Gateway Unit, No. 1	T. 15 S., R. 104 W, sec. 15 19	Mesa.
143	Continental Oil Company	Ute Mountain, No. 1	T. 32 N., R. 19 W., sec. 07 04	Montezuma.
144	Davis Oil Company	Red Mesa Deep, No. 1	T. 33 N., R. 12 W., sec. 23 06	La Plata.
145	Skelly Oil Company	Lloyd Benton, No. 1	T. 33 N., R. 13 W., sec. 15 07	La Plata.
146	California Oil Company	Ute Mountain Tribal, No. 1	T. 33 N., R. 18 W., sec. 22 16	Montezuma.
147	General Petroleum Corporation	Kikel, No. 55-17	T. 34 N., R. 11 W., sec. 17 10	La Plata.
148	El Paso Natural Gas Company	Butler Pool Unit 1, No. 44-28	T. 34 N., R. 12 W., sec. 28 06	La Plata.
149	Houston Oil & Minerals Corporation	Ute Mountain, No. 44-34	T. 34 N., R. 14 W., sec. 34 16	Montezuma.
150	Davis Oil Company	Peaker Government, No. 1	T. 36 N., R. 12 W., sec. 32 03	Montezuma.
151	Reynolds Mining Corporation	Point Lookout, No. 1	T. 36 N., R. 14 W., sec. 18 09	Montezuma.
152	Shell Oil Company	Federal 23-36-17, No. 1	T. 36 N., R. 17 W., sec. 23 16	Montezuma.
153	Shell Oil Company	Federal 9-36-18, No. 1	T. 36 N., R. 18 W., sec. 09 08	Montezuma.
154	Read & Stevens Inc	Shenandoah Veach, No. 1	T. 37 N., R. 15 W., sec. 02 13	Montezuma.
155	Shell Oil Company	State, No. 1	T. 37 N., R. 16 W., sec. 04 16	Montezuma.
156	Gulf Oil Corporation	Fulks, No. 1	T. 37 N., R. 17 W., sec. 27 04	Montezuma.
157	Shell Oil Company	Federal 36-37-18, No. 1	T. 37 N., R. 18 W., sec. 36 09	Montezuma.
158	Hathaway Company	USC, No. 1	T. 37 N., R. 20 W., sec. 11 15	Montezuma.
159	Gulf Energy & Minerals Company	Dolores River Unit, No. 1	T. 38 N., R. 13 W., sec. 02 15	Montezuma.
160	Stuarco Oil Company	Federal Tully, No. 1	T. 38 N., R. 13 W., sec. 18 14	Montezuma.
161	Great Western Drilling Company	Tully State, No. 1	T. 38 N., R. 14 W., sec. 18 14	Montezuma.
162	Mobil Oil Company	Cow Canyon Unit, No. 1	T. 38 N., R. 19 W., sec. 13 04	Montezuma.
163	Gulf Oil Corporation	S. Stoner Creek Federal, No. 2	T. 39 N., R. 12 W., sec. 18 01	Dolores.
164	California Oil Company	Stoner Creek Unit, No. 1	T. 39 N., R. 13 W., sec. 18 07	Dolores.
165	California Oil Company	House Creek Unit, No. 1	T. 39 N., R. 14 W., sec. 19 12	Montezuma.
166	Davis Oil Company	Squaw Canyon Federal, No. 2	T. 39 N., R. 19 W., sec. 18 05	Dolores.
167	Santa Fe Energy Company	Narraguinnep Federal, No. 1-35	T. 40 N., R. 16 W., sec. 35 12	Dolores.
168	Sinclair Oil & Gas Company	Glade Canyon Unit, No. 1	T. 40 N., R. 17 W., sec. 13 01	Dolores.
169	Shell Oil Company	Doe Canyon Unit, No. 1	T. 40 N., R. 18 W., sec. 15 01	Dolores.
170	Montex Drilling Company	Mark's Draw Unit, No. 27-1	T. 41 N., R. 13 W., sec. 27 01	Dolores.
171	W A Moncrief, et al	Hunt Creek Unit, No. 10-1	T. 41 N., R. 15 W., sec. 10 09	Dolores.
172	Continental Oil Company	Big Canyon Unit, No. 1	T. 41 N., R. 18 W., sec. 17 16	Dolores.
173	Read & Stevens Inc	Shenandoah Pinto, No. 1-X	T. 42 N., R. 18 W., sec. 34 06	Dolores.
174	Exxon Company USA	Thomas Mountain Federal, No. 1	T. 43 N., R. 15 W., sec. 12 04	San Miguel.
175	Read & Stevens Inc	Slick Rock Federal, No. 1	T. 43 N., R. 17 W., sec. 08 09	San Miguel.
176	Reynolds Mining Corporation	Egnar, No. 1	T. 43 N., R. 19 W., sec. 14 04	San Miguel.
177	Amoco Production Company	Naturita Creek Unit, No. 1	T. 44 N., R. 13 W., sec. 34 03	San Miguel.
178	Union Oil Company of California	SE Lisbon USA, No. 3	T. 44 N., R. 19 W., sec. 16 05	San Miguel.
179	Belco Petroleum Corporation	Egnar Unit, No. 1	T. 44 N., R. 19 W., sec. 30 08	San Miguel.
180	Whitlock L E	Swanson, No. 1-A	T. 45 N., R. 08 W., sec. 15 01	Ouray.

Appendix 1. Drill holes used as control points for maps and cross sections—*Continued.*

No.	Company	Well name	Location	County
		COLORADO—*Continued*		
181	Davis Oil Company	McClure, No. 1	T. 45 N., R. 09 W., sec. 30 06	Ouray.
182	Shell Oil Company	Shell Federal, No. 21-19	T. 45 N., R. 13 W., sec. 19 03	San Miguel.
183	Union Oil Company of California	Montrose Unit, No. 2	T. 45 N., R. 16 W., sec. 05 15	Montrose.
184	Anadarko Production Company	Hamm Canyon Unit, No. 1	T. 45 N., R. 18 W., sec. 26 13	San Miguel.
185	Shell Oil Company	Gypsum Valley West, No. 1	T. 45 N., R. 19 W., sec. 26 09	San Miguel.
186	Miami Oil Producers Inc	Kirby Government, No. 1	T. 47 N., R. 15 W., sec. 10 06	Montrose.
187	Shell Oil Company	Wray Mesa Unit, No. 1	T. 47 N., R. 19 W., sec. 21 15	Montrose.
188	Humble Oil & Refining Company	Uravan Government, No. 1	T. 48 N., R. 17 W., sec. 26 06	Montrose.
189	Mobil Oil Corporation	Moon Mesa Unit, No. 1	T. 49 N., R. 16 W., sec. 31 13	Montrose.
190	Husky Oil Company	Sinbad Valley Unit, No. 2	T. 49 N., R. 19 W., sec. 15 09	Mesa.
		NEW MEXICO		
191	Texaco Inc	Navajo Tribe AO, No. 1	T. 25 N., R. 19 W., sec. 33 01	San Juan.
192	Texaco Inc	Navajo Tribe Al, No. 1	T. 26 N., R. 18 W., sec. 28 08	San Juan.
193	Amerada Hess Corporation	Navajo 4, No. 1	T. 27 N., R. 17 W., sec. 20 03	San Juan.
194	Humble Oil & Refining Company	Navajo, No. 2-1	T. 29 N., R. 15 W., sec. 18 13	San Juan.
195	Stanolind Oil and Gas Company	USG, No. 13	T. 29 N., R. 16 W., sec. 19 07	San Juan.
196	Pan American Petroleum Corporation	Hoover, No. 1-A	T. 30 N., R. 16 W., sec. 23 05	San Juan.
197	Pan American Petroleum Corporation	Navajo Tribal AD, No. 1	T. 30 N., R. 21 W., sec. 13 07	San Juan.
198	Amoco Production Company	Ute Mountain Gas Com D, No. 1	T. 31 N., R. 14 W., sec. 10 06	San Juan.
199	Reynolds Mining Corporation	Chimney Rock, No. 1	T. 31 N., R. 17 W., sec. 22 06	San Juan.
200	Humble Oil & Refining Company	Navajo C, No. 1	T. 31 N., R. 18 W., sec. 08 01	San Juan.
201	British American Oil Producing Co	Navajo E, No. 1	T. 31 N., R. 20 W., sec. 15 06	San Juan.
202	Continental Oil Company	Navajo 21, No. 1	T. 32 N., R. 19 W., sec. 21 16	San Juan.

Appendix 2. Outcrops used as control points for maps and cross sections.

[Table is sorted by township, range, and section within States]

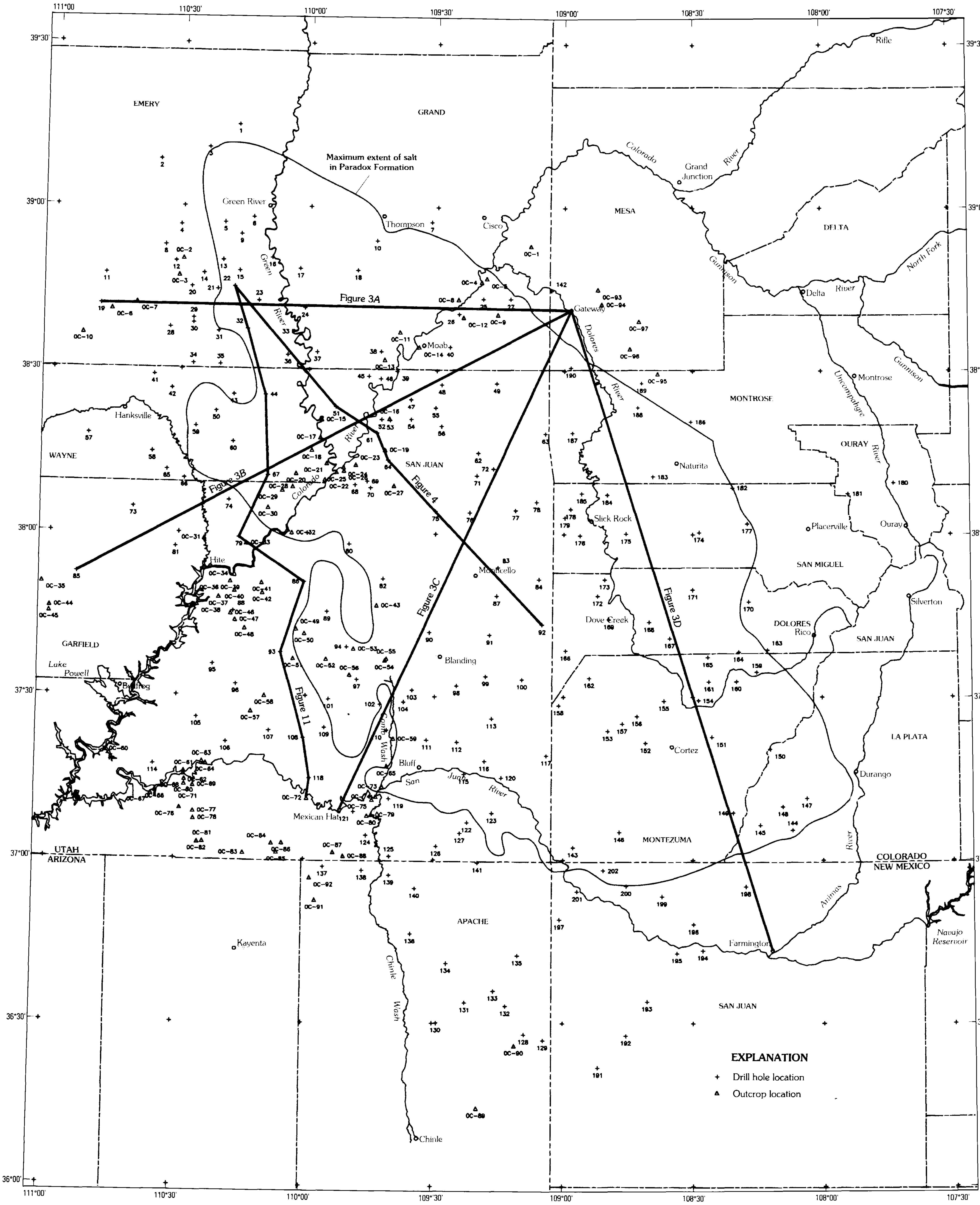
Number	Location	County	Unit measured	Source
			UTAH	
OC-1	T. 22 S., R. 25 E., sec. 22	Grand	Cutler Formation	Dane, 1935.
OC-2	T. 23 S., R. 13 E., sec. 04	Emery	Kaibab Limestone	Baker, 1946.
OC-3	T. 23 S., R. 13 E., sec. 29	Emery	Kaibab Limestone	Stewart and others, 1972.
OC-4	T. 23 S., R. 23 E., sec. 25	Grand	Kaibab Limestone, White Rim Sandstone	Stewart and others, 1972.
OC-5	T. 23 S., R. 24 E., sec. 30	Grand	Kaibab Limestone, White Rim Sandstone	Dane, 1935.
OC-6	T. 24 S., R. 10 E., sec. 35	Emery	Kaibab Limestone	Baker, 1946.
OC-7	T. 24 S., R. 11 E., sec. 26	Emery	Kaibab Limestone	Stewart and others, 1972.
OC-8	T. 24 S., R. 23 E., sec. 18	Grand	Kaibab Limestone, White Rim Sandstone	Dane, 1935.
OC-9	T. 24 S., R. 24 E., sec. 34	Grand	Kaibab Limestone, White Rim Sandstone, Cutler Formation	Dane, 1935.
OC-10	T. 25 S., R. 09 E., sec. 26	Emery	Kaibab Limestone	Hunt and others, 1953.
OC-11	T. 25 S., R. 21 E., sec. 19	Grand	Kaibab Limestone, White Rim Sandstone	Stewart and others, 1972.
OC-12	T. 25 S., R. 23 E., sec. 05	Grand	Kaibab Limestone, White Rim Sandstone	Shoemaker and Newman, 1959.
OC-13	T. 26 S., R. 20 E., sec. 22	Grand	Kaibab Limestone, White Rim Sandstone	McKnight, 1940.
OC-14	T. 26 S., R. 21 E., sec. 02	Grand	Kaibab Limestone, White Rim Sandstone	McKnight, 1940.
OC-15	T. 28 S., R. 18 E., sec. 21	San Juan	White Rim Sandstone	McKnight, 1940.
OC-16	T. 28 S., R. 20 E., sec. 23	San Juan	White Rim Sandstone	Stewart and others, 1972.
OC-17	T. 29 S., R. 18 E., sec. 16	Wayne	White Rim Sandstone	Baker, 1946.
OC-18	T. 29 S., R. 18 E., sec. 31	Wayne	Organ Rock Formation	Baker, 1946.
OC-19	T. 29 S., R. 20 E., sec. 27	San Juan	White Rim Sandstone	Baker, 1946.
OC-20	T. 30 S., R. 17 E., sec. 22	Wayne	Organ Rock Formation	Baker, 1946.
OC-21	T. 30 S., R. 18 E., sec. 11	Wayne	White Rim Sandstone	Baker, 1946.
OC-22	T. 30 S., R. 18 E., sec. 34	Wayne	Cedar Mesa Sandstone, Rico Formation	Baker, 1946.
OC-23	T. 30 S., R. 19 E., sec. 02	San Juan	Cedar Mesa Sandstone	Baker, 1946.
OC-24	T. 30 S., R. 19 E., sec. 05	San Juan	Rico Formation	McKnight 1940.
OC-25	T. 30 S., R. 19 E., sec. 07	San Juan	Rico Formation	Baker and Reeside, 1929.
OC-26	T. 30 S., R. 19 E., sec. 09	San Juan	Lower Cutler beds	Loope and others, 1990.
OC-27	T. 30 S., R. 21 E., sec. 30	San Juan	White Rim Sandstone, Organ Rock Formation	Stewart and others, 1972.
OC-28	T. 30½ S., R. 17 E., sec. 28	Garfield	White Rim Sandstone, Organ Rock Formation	Stewart and others, 1972.
OC-29	T. 30½ S., R. 17 E., sec. 31	Garfield	White Rim Sandstone, Organ Rock Formation	Baker, 1946.
OC-30	T. 31 S., R. 16 E., sec. 16	Garfield	White Rim Sandstone	Baker, 1946.
OC-31	T. 32 S., R. 14 E., sec. 31	Garfield	White Rim Sandstone, Organ Rock Formation	Baker, 1946.
OC-32	T. 32 S., R. 17 E., sec. 16	San Juan	Rico Formation	Baker and Reeside, 1929.
OC-33	T. 32½ S., R., 15 E., sec. 26	Garfield	Organ Rock Formation	Baker, 1946.

Appendix 2. Outcrops used as control points for maps and cross sections—*Continued.*

Number	Location	County	Unit measured	Source
			UTAH—*Continued*	
OC-34	T. 33 S., R. 14 E., sec. 20	Garfield	White Rim Sandstone, Organ Rock Formation	Baker, 1946.
OC-35	T. 34 S., R. 08 E., sec. 21	Garfield	Kaibab Limestone	Davidson, 1967.
OC-36	T. 34 S., R. 13 E., sec. 36	San Juan	White Rim Sandstone	Thaden and others, 1964.
OC-37	T. 34 S., R. 14 E., sec. 24	San Juan	White Rim Sandstone	Cooley, 1965.
OC-38	T. 34 S., R. 14 E., sec. 31	San Juan	White Rim Sandstone	Stewart and others, 1972.
OC-39	T. 34 S., R. 15 E., sec. 05	San Juan	Organ Rock Formation	Thaden and others, 1964.
OC-40	T. 34 S., R. 15 E., sec. 16	San Juan	Organ Rock Formation	Thaden and others, 1964.
OC-41	T. 34 S., R. 16 E., sec. 04	San Juan	Rico Formation	Thaden and others, 1964.
OC-42	T. 34 S., R. 16 E., sec. 16	San Juan	Cedar Mesa Sandstone	Thaden and others, 1964.
OC-43	T. 34 S., R. 20 E., sec. 33	San Juan	Organ Rock Formation	Stewart and others, 1972.
OC-44	T. 35 S., R. 08 E., sec. 14	Garfield	Kaibab Limestone	Davidson, 1967; Hunt & others, 1953.
OC-45	T. 35 S., R. 08 E., sec. 23	Garfield	Kaibab Limestone	Davidson, 1967.
OC-46	T. 35 S., R. 15 E., sec. 08	San Juan	White Rim Sandstone	Thaden and others, 1964.
OC-47	T. 35 S., R. 15 E., sec. 16	San Juan	Organ Rock Formation	Thaden and others, 1964.
OC-48	T. 35 S., R. 15 E., sec. 26	San Juan	Organ Rock Formation	Stewart and others, 1972.
OC-49	T. 35 S., R. 17 E., sec. 27	San Juan	Organ Rock Formation	Finnell and others, 1963.
OC-50	T. 35 S., R. 17 E., sec. 36	San Juan	Organ Rock Formation	Gregory, 1938.
OC-51	T. 36 S., R. 17 E., sec. 33	San Juan	Organ Rock Formation	Finnell and others, 1963.
OC-52	T. 36 S., R. 18 E., sec. 34	San Juan	Organ Rock Formation	Stewart and others, 1972.
OC-53	T. 36 S., R. 19 E., sec. 15	San Juan	Organ Rock Formation	Gregory, 1938.
OC-54	T. 36 S., R. 20 E., sec. 34	San Juan	Organ Rock Formation	Gregory, 1938.
OC-55	T. 36 S., R. 20 E., sec. 35	San Juan	Organ Rock Formation	Stewart and others, 1972.
OC-56	T. 37 S., R. 19 E., sec. 16	San Juan	Organ Rock Formation	Gregory, 1938.
OC-57	T. 38 S., R. 15 E., sec. 25	San Juan	Organ Rock Formation	Gregory, 1938.
OC-58	T. 38 S., R. 16 E., sec. 09	San Juan	Organ Rock Formation	Mullens, 1960.
OC-59	T. 39 S., R. 20 E., sec. 25	San Juan	De Chelly Sandstone	Sears, 1956.
OC-60	T. 40 S., R. 10 E., sec. 11	San Juan	Kaibab Limestone	Stewart and others, 1972.
OC-61	T. 40 S., R. 13 E., sec. 34	San Juan	De Chelly Sandstone	Mullens, 1960.
OC-62	T. 40 S., R. 14 E., sec. 20	San Juan	Organ Rock Formation	Mullens, 1960.
OC-63	T. 40 S., R. 14 E., sec. 27	San Juan	De Chelly Sandstone	Baker and Reeside, 1929.
OC-64	T. 40 S., R. 20 E., sec. 26	San Juan	Organ Rock Formation	Sears, 1956.
OC-65	T. 40 S., R. 20 E., sec. 26	San Juan	Cedar Mesa Sandstone	Sears, 1956.
OC-66	T. 41 S., R. 12 E., sec. 22	San Juan	De Chelly Sandstone, Organ Rock Formation	Baker and Reeside, 1929; Baker, 1936.

Appendix 2. Outcrops used as control points for maps and cross sections—*Continued.*

Number	Location	County	Unit measured	Source
			UTAH—*Continued*	
OC-67	T. 41 S., R. 12 E., sec. 28	San Juan	Organ Rock Formation	Read and Wanek, 1961.
OC-68	T. 41 S., R. 13 E., sec. 10	San Juan	Organ Rock Formation	Stewart and others, 1972.
OC-69	T. 41 S., R. 13 E., sec. 13	San Juan	Organ Rock Formation	Baker, 1936.
OC-70	T. 41 S., R. 13 E., sec. 15	San Juan	Organ Rock Formation	Read and Wanek, 1961.
OC-71	T. 41 S., R. 13 E., sec. 23	San Juan	De Chelly Sandstone	Baker, 1936.
OC-72	T. 41 S., R. 17 E., secs. 34, 36	San Juan	Rico Formation and Halgaito Formation	Baker, 1936.
OC-73	T. 41 S., R. 20 E., sec. 15	San Juan	Organ Rock Formation	Baker, 1936.
OC-74	T. 41 S., R. 20 E., sec. 28	San Juan	De Chelly Sandstone	O'Sullivan, 1965.
OC-75	T. 41 S., R. 20 E., sec. 32	San Juan	De Chelly Sandstone, Organ Rock Fm., Cedar Mesa Sandstone	Stewart and others, 1972.
OC-76	T. 42 S., R. 13 E., sec. 09	San Juan	De Chelly Sandstone	Baker, 1936.
OC-77	T. 42 S., R. 13 E., sec. 12	San Juan	Organ Rock Formation	Baker and Reeside, 1929.
OC-78	T. 42 S., R. 13 E., sec. 24	San Juan	De Chelly Sandstone, Organ Rock Formation	Read and Wanek, 1961.
OC-79	T. 42 S., R. 20 E., sec. 17	San Juan	Organ Rock Formation	O'Sullivan, 1965.
OC-80	T. 42 S., R. 20 E., sec. 18	San Juan	Cedar Mesa Sandstone	O'Sullivan, 1965.
OC-81	T. 43 S., R. 14 E., sec. 17	San Juan	De Chelly Sandstone, Organ Rock Formation	Baker, 1936.
OC-82	T. 43 S., R. 14 E., sec. 18	San Juan	De Chelly Sandstone, Organ Rock Formation	Read and Wanek, 1961.
OC-83	T. 43 S., R. 15 E., sec. 26	San Juan	De Chelly Sandstone	Baker, 1936.
OC-84	T. 43 S., R. 16 E., sec. 14	San Juan	De Chelly Sandstone	Baker, 1936.
OC-85	T. 43 S., R. 16 E., sec. 25	San Juan	De Chelly Sandstone, Organ Rock Formation	Read and Wanek, 1961.
OC-86	T. 43 S., R. 17 E., sec. 18	San Juan	Organ Rock Formation	Baker, 1936.
OC-87	T. 43 S., R. 18 E., sec. 25	San Juan	Cedar Mesa Sandstone	O'Sullivan, 1965.
OC-88	T. 43 S., R. 19 E., sec. 32	San Juan	De Chelly Sandstone, Organ Rock Formation	O'Sullivan, 1965.
			ARIZONA	
OC-89	T. 06 N., R. 08 E., sec. 15	Apache	De Chelly Sandstone	Read and Wanek, 1961.
OC-90	T. 08 N., R. 07 E., sec. 12	Apache	De Chelly Sandstone	Stewart and others, 1972.
OC-91	T. 40 N., R. 22 E., sec. 13	Apache	De Chelly Sandstone, Organ Rock Formation	Read and Wanek, 1961.
OC-92	T. 41 N., R. 22 E., sec. 22	Apache	De Chelly Sandstone, Organ Rock Formation	Witkind and Thaden, 1963.
			COLORADO	
OC-93	T. 15 S., R., 103 W., sec. 14	Mesa	Cutler Formation	Cater, 1970.
OC-94	T. 15 S., R., 103 W., sec. 36	Mesa	Cutler Formation	Cater, 1970.
OC-95	T. 49 S., R. 16 E., sec. 22	Montrose	Cutler Formation	Cater, 1970.
OC-96	T. 50 S., R. 17 E., sec. 27	Mesa	Cutler Formation	Cater, 1970.
OC-97	T. 51 S., R. 17 E., sec. 25	Mesa	Cutler Formation	Cater, 1970.



Digital Geologic data prepared with
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VAX/VMS 5.4.3

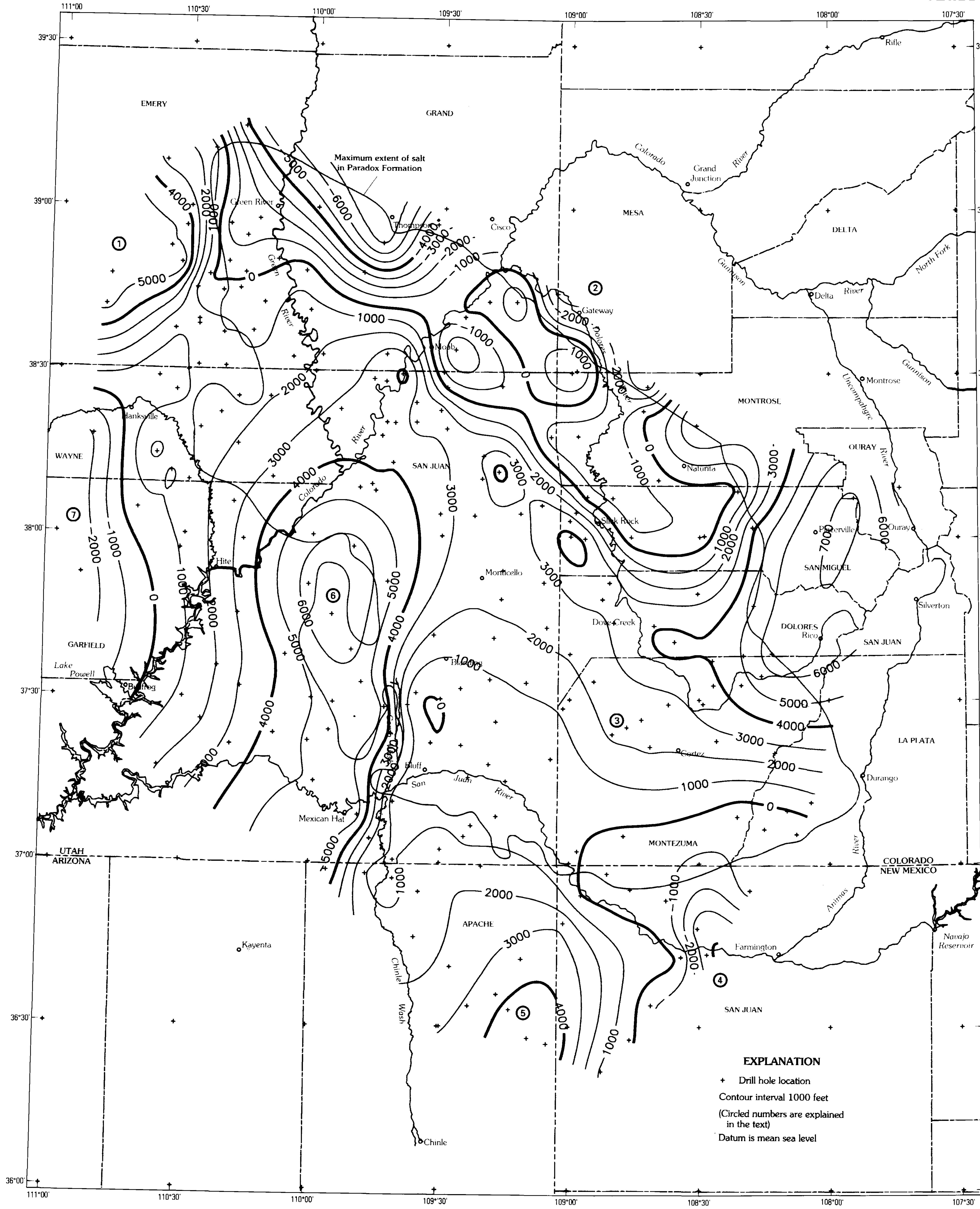
0 25 50 MILES
0 25 50 KILOMETERS

MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING LOCATIONS OF DRILL HOLES AND OUTCROPS USED FOR THIS STUDY, AND LINES OF SECTION SHOWN IN FIGURES 3, 4, AND 11

By

Steven M. Condon

1997



Digital Geologic data prepared with
Interactive Surface Modeling running under
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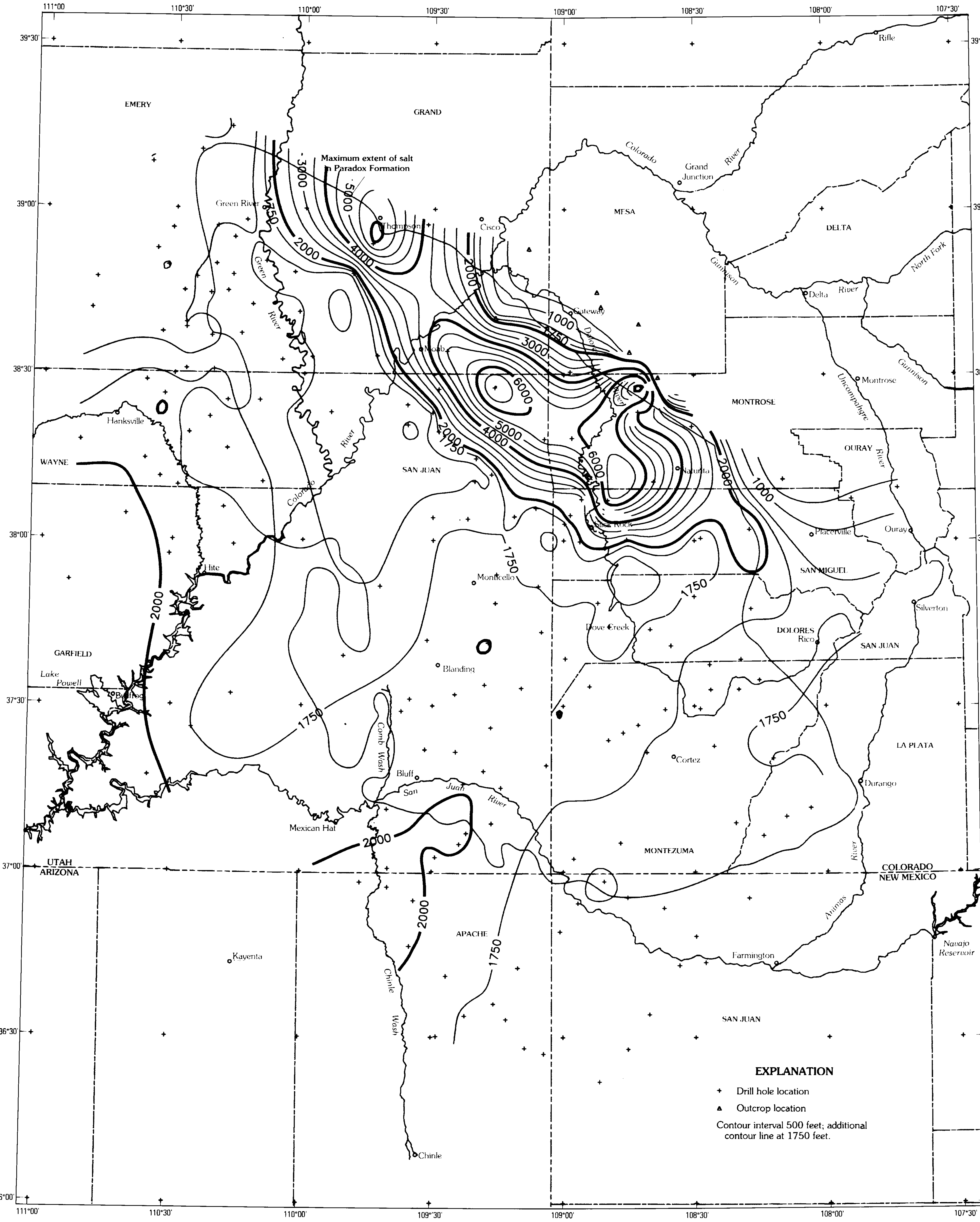
VAX/VMS 5.4.3

0 25 50 MILES
0 25 50 KILOMETERS

MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING STRUCTURE CONTOURS DRAWN ON THE BASE OF THE CUTLER GROUP OR FORMATION

By
Steven M. Condon

1997

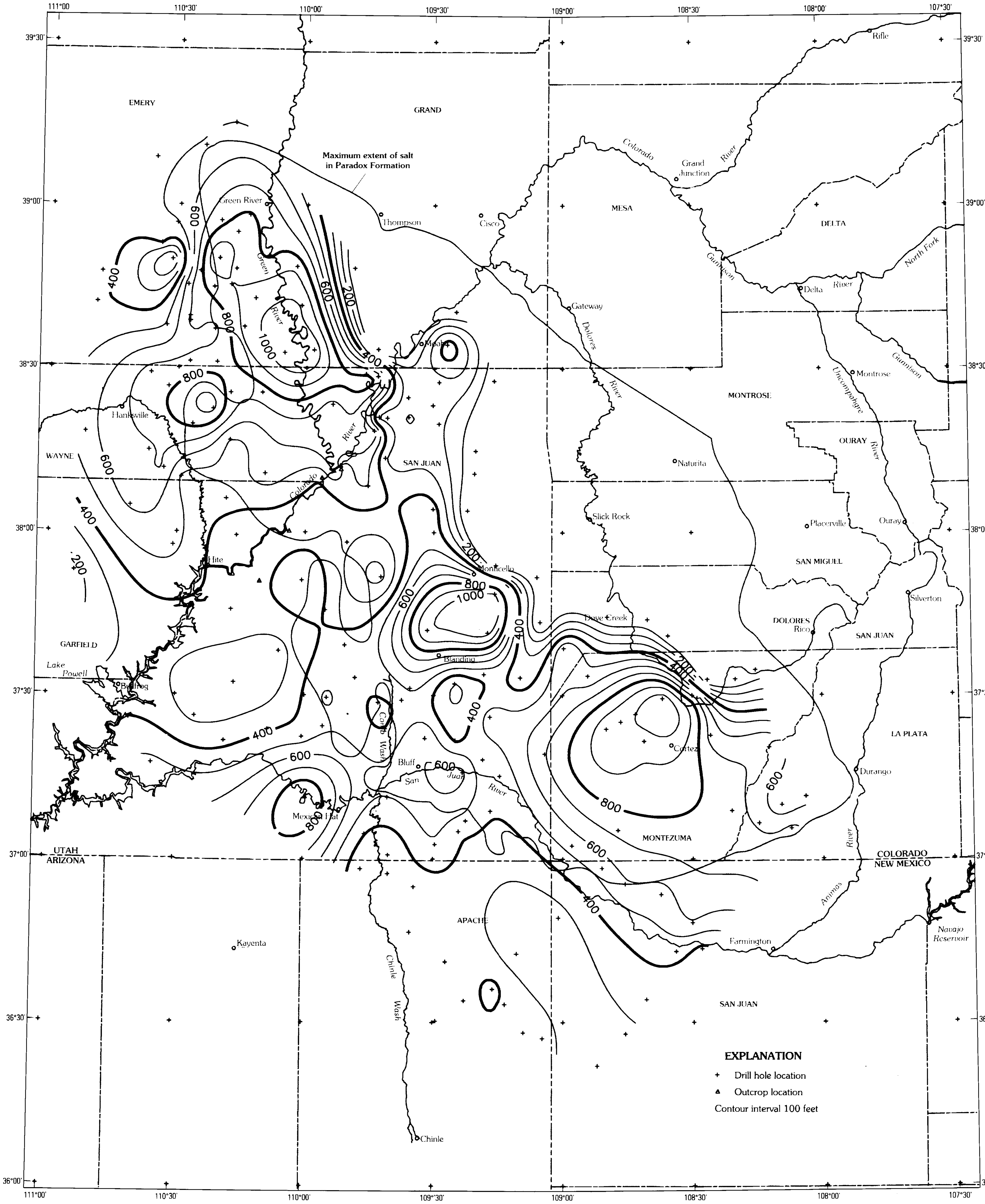


Digital Geologic data prepared with Interactive Surface Modeling running under DG/UX 5.4R2.01 on a Unix workstation under VAX/VMS 5.4.3

MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING THICKNESS OF THE PENNSYLVANIAN AND PERMIAN CUTLER GROUP OR FORMATION

By
Steven M. Condon

1997



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0 25 50 MILES
0 25 50 KILOMETERS

MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING THICKNESS OF THE PENNSYLVANIAN AND PERMIAN LOWER CUTLER BEDS

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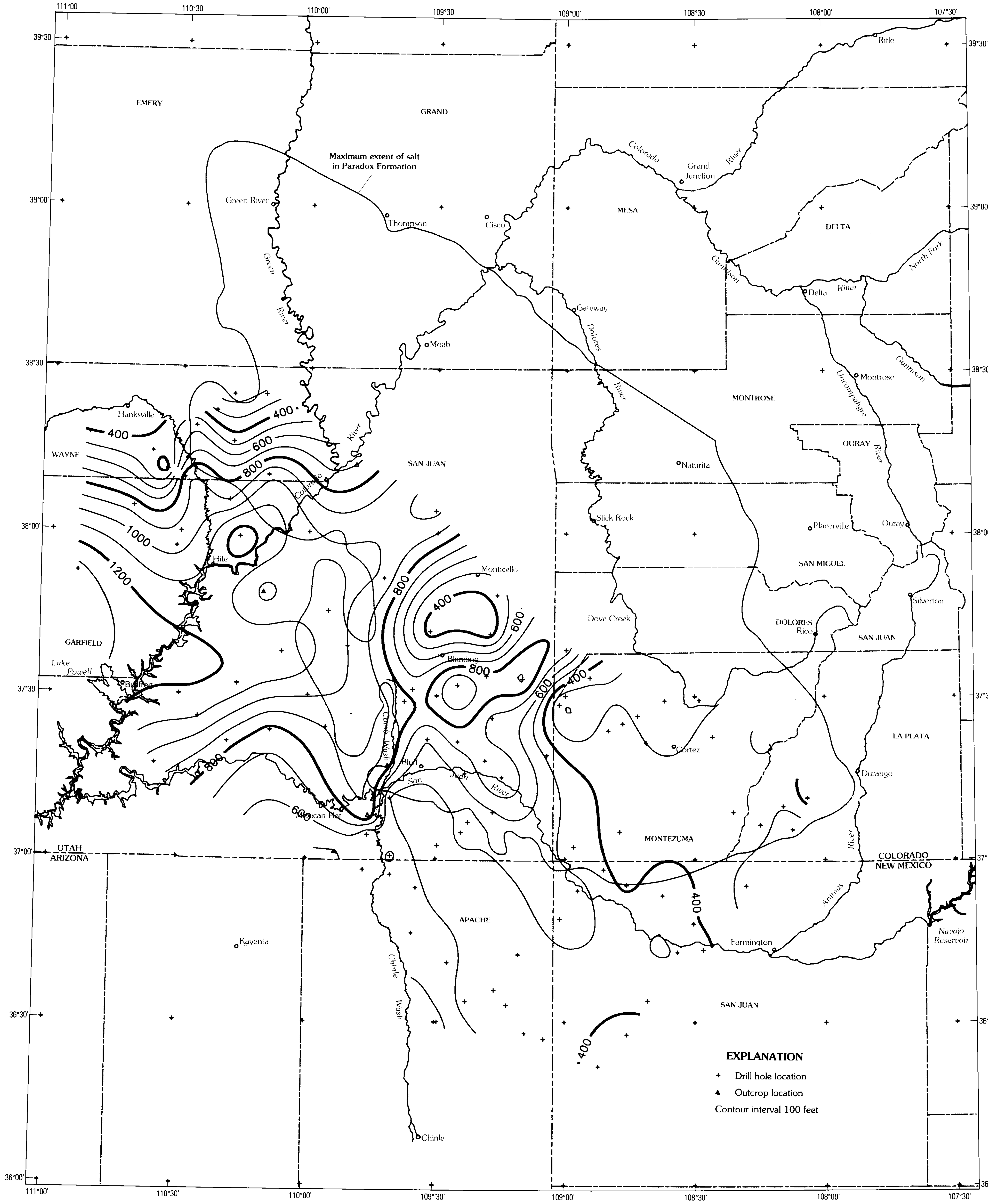

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MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING THICKNESS OF THE PERMIAN CEDAR MESA SANDSTONE

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Steven M. Condon
1997

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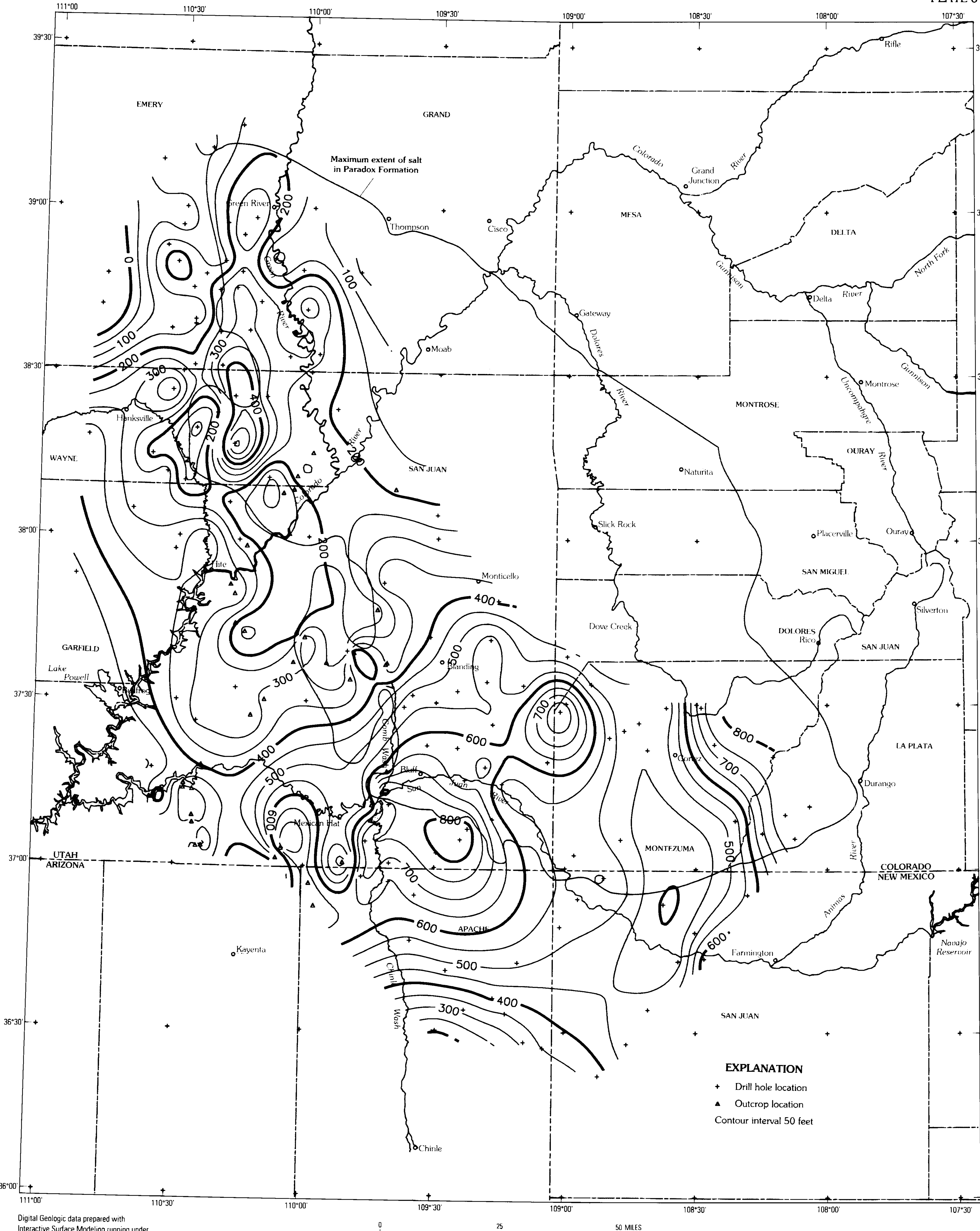
PLATE 6



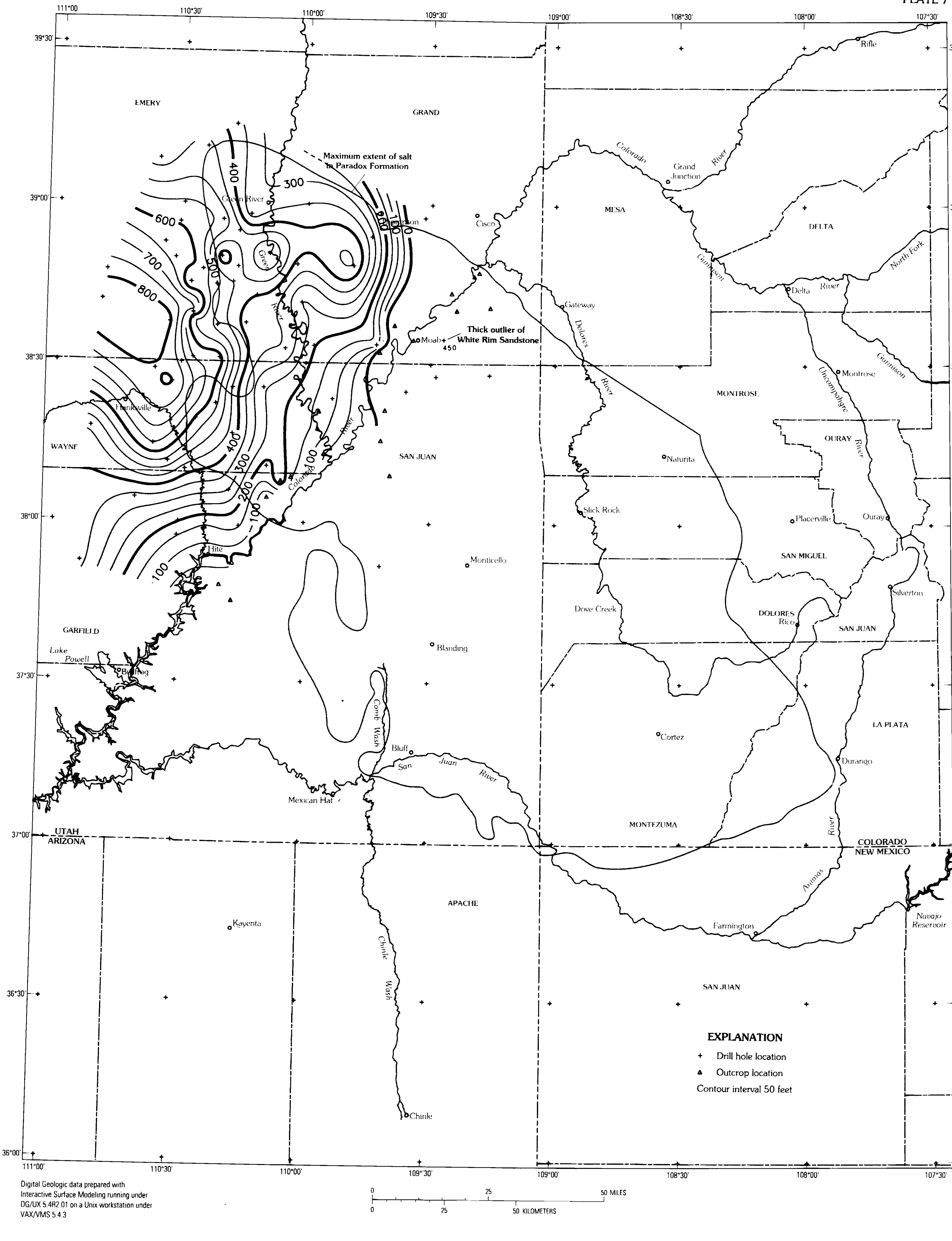
Digital Geologic data prepared with Interactive Surface Modeling running under DG/UX 5.4R2.01 on a Unix workstation under VAX/VMS 5.4.3

0 25 50 MILES
0 25 50 KILOMETERS

MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING THICKNESS OF THE PERMIAN ORGAN ROCK FORMATION

By
Steven M. Condon

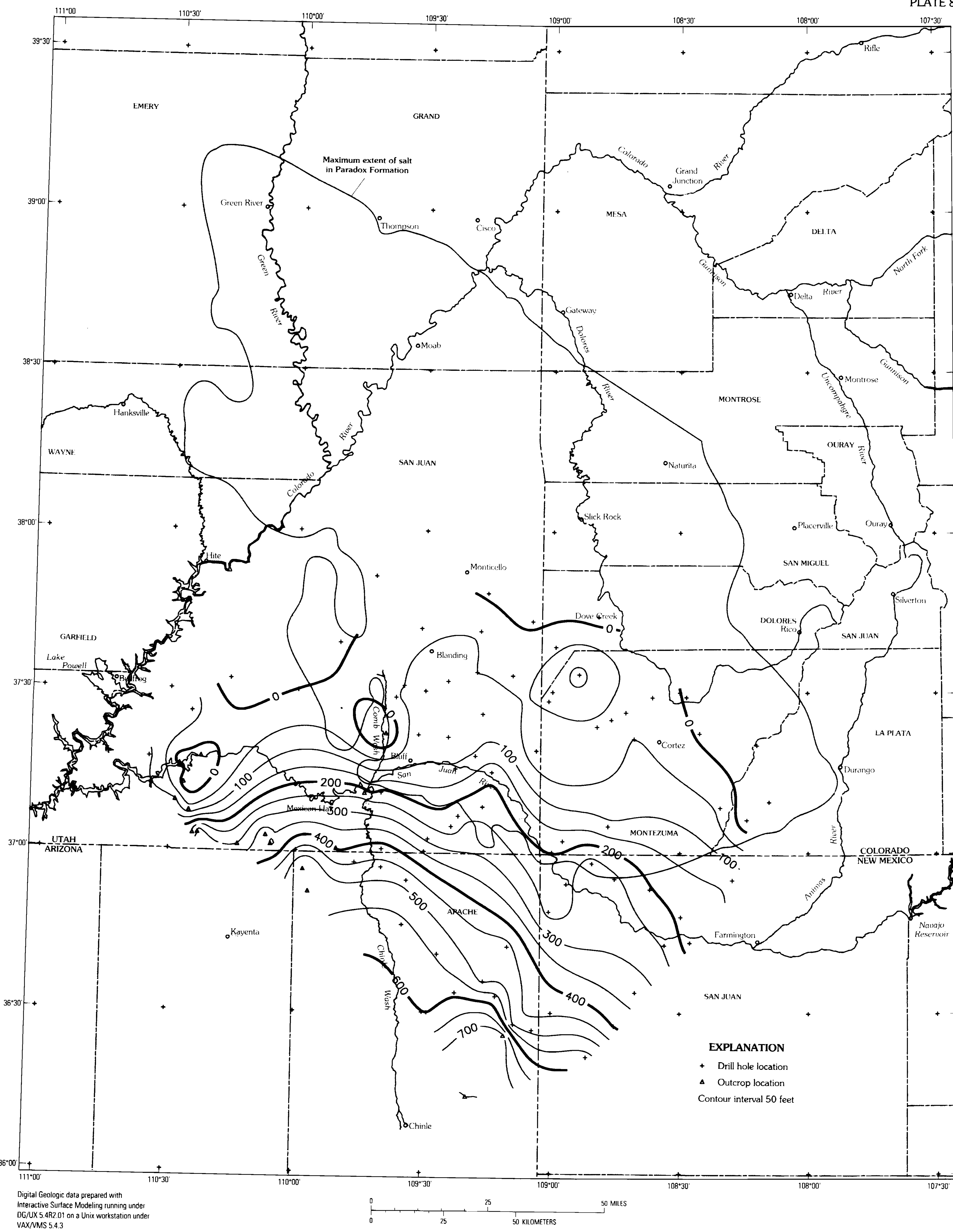
1997



Digital Geologic data prepared with Interactive Surface Modeling running under DG/UX 5.4R2.01 on a Unix workstation under VAX/VMS 5.4.3

MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING THICKNESS OF THE PERMIAN WHITE RIM SANDSTONE

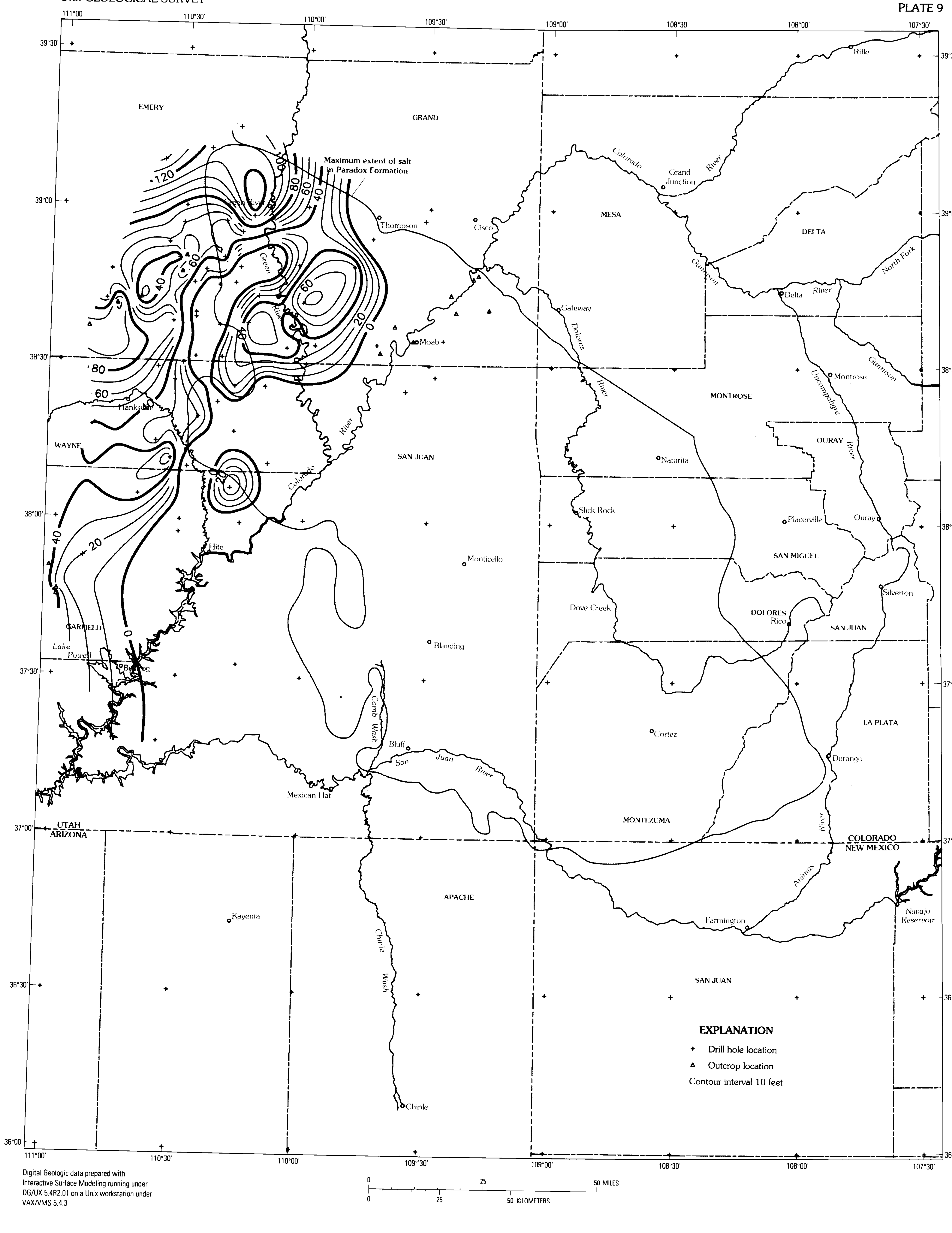
By
Steven M. Condon
1997



MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING THICKNESS OF THE PERMIAN DE CHELLY SANDSTONE

By
Steven M. Condon

1997



MAP OF THE PARADOX BASIN AND ADJACENT AREAS SHOWING THICKNESS OF THE PERMIAN KAIBAB LIMESTONE

By
Steven M. Condon
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